Arnold Schwarzenegger
Governor

DURABILITY AND RELIABILITY DEMONSTRATION OF A NEAR-ZERO-EMISSION GAS-FIRED POWER PLANT

PIER FINAL PROJECT REPORT

Prepared For:
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DISCLAIMER

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The authors personally acknowledge the untiring efforts of Mr. Terry Chiles, Manager of the Kimberlina Power Plant, and his staff. They breathed new life into a biomass power plant idled since 1987, installed new subsystems to transform the plant into the world's cleanest fossil-fueled power generator, and operated and maintained the plant from startup through more than 400 hot tests and 1,300 hours of gas generator operation.

Citation

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity RD&D, and $12 million or more annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

Durability and Reliability Demonstration of a Near-Zero-Emission, Gas-Fired Power Plant is the final report for the Kimberlina near-zero-emission, gas-fired power plant project (Contract Number 500-01-013) conducted by Clean Energy Systems, Inc. The information from this project contributes to PIER's Environmentally Preferred Advanced Generation research program.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier, or contact the Energy Commission at (916) 654-5164.

Abstract

Purpose

- Demonstrate an innovative power generation combustion system, developed by Clean Energy Systems, Inc. (CES), that provides an enabling technology for gas-fired power plants to produce electricity with zero emissions: emit no criteria pollutants, and cost-effectively capture CO_2 to mitigate the global warming impact of this greenhouse gas.

Objectives

- Demonstrate the durability and reliability of the CES oxy-fuel combustor, called a *gas generator* (GG), at a grid-connected power plant near Bakersfield, California.
- Operate the GG under steady-state and off-design conditions to establish acceptable operating limits, while exporting electricity to the grid.
- Monitor nitrogen oxide (NOx) and carbon monoxide (CO) emissions, and determine design changes and operating procedures that will further reduce the low emissions.

Results

- The GG was commissioned with no limiting factors, and all plant subsystems were successfully renovated and calibrated. Electricity generation and export were achieved.
- The GG operated more than 1,300 hours over nine months with 95% availability. It was easy to start, easy to control, and stable over a broad range of operating parameters.

Conclusions

- The reliability of the GG was excellent.
- NOx and CO emissions, without exhaust clean-up, were near or below southern California BACT limits for gas turbine generation systems recently permitted with SCR.

Recommendations

- Modify hardware and operating procedures to further reduce NOx and CO emissions.
- Conduct GG testing on syngas for operation on landfill gas, biogas, and gasified coal.
- Match the GG with high temperature gas turbine technology for improved efficiency and peaker power plant applications.

Benefit to California

- The CES system enables gas-fired, zero-emission, base load power generation with efficient capture of CO_2 for sequestration or enhanced oil recovery (EOR).
- The CES technology can be used in ultra low emissions peaker power plants without the use of selective catalytic reduction (SCR).

Executive Summary

Introduction

This project demonstrated a novel power generation combustion system that provides an enabling technology for fossil-fueled power plants to produce zero emissions – to emit no criteria pollutants, and to cost-effectively capture CO_2 to mitigate the global warming impact of this greenhouse gas.

The project demonstrated the durability and reliability of a oxy-fuel combustion system, designed, manufactured and tested by Clean Energy Systems, Inc. (CES). Over the period of a year, CES operated the system in a demonstration power plant and exported electricity to the grid. The unique combustor, called a *gas generator* (GG), burns gaseous fuel in oxygen (not air) to produce a drive gas composed of steam and carbon dioxide (CO_2), which powers a steam turbine and electrical generator. The steam is condensed leaving an exhaust gas that is nearly pure CO_2, which can be sequestered or used for industrial purposes.

With investor capital and support from the U.S. Department of Energy's Vision 21 Program, CES developed and successfully demonstrated a 20 megawatt thermal (MW_t) gas generator (Figure ES-1). To improve utility industry confidence in the durability and reliability of the GG under actual, grid-connected power plant conditions, CES acquired an idle 5.5 megawatt electric (MW_e) biomass power plant (Kimberlina Power Plant [KPP], Figure ES-2) near Bakersfield, California, as a site for durability testing of the GG.

Figure ES-1. Gas Generator **Figure ES-2. Kimberlina Power Plant**

With support from the California Energy Commission's Public Interest Energy Research (PIER) program, CES updated the power plant to include oxygen, natural gas, and demineralized feedwater systems, designed and manufactured a high-speed control system for the GG, and installed the GG and its control system in the plant. The GG replaced the plant's biomass-fired boiler as a steam source for the turbo-generator. Because of the retrofit nature of the project, power output from the 20 MW_t (~10MW_e) GG was constrained to the 5.5 MW_t maximum capacity of the existing steam turbine.

Purpose

Broadly speaking, the purpose of this project was to demonstrate a promising technology that would enable gas-fired power plants to produce ultra low emissions, or zero emissions with the capture of CO_2. The unique combustion system provides a drive gas that is primarily steam (90%) and CO_2 (10%) with capture of non-condensable gases in a geothermal type condenser. Consequently, minimal CO_2 separation technology is required, primarily additional water separation and compression of the CO_2 for sequestration or commercial use.

Additionally, the project was to demonstrate that the CES GG has high reliability, availability, maintainability, durability, and usability, by way of a sustained, real-world demonstration under actual operating conditions. To dispel utility industry concerns on the technology's maturity, CES demonstrated the GG for over a year in a grid-connected power plant. Secondary objectives included validating GG and plant operating procedures and determining design changes that could improve GG and/or plant reliability and durability.

Project Technical Objectives

The technical objectives of the project were divided into three phases, and were all successfully completed:

- **System/Plant Commissioning**
    - Install and commission CES GG and control system.
    - Renovate, calibrate, and repair existing KPP subsystems.
    - Add high-pressure O_2, NG, and DI water subsystems.
    - Upgrade plant safety and security systems to meet current standards.
    - Operationally test, and formally commission, each subsystem.
- **Normal Steady-State Operations**
    - Operate GG and plant subsystems with runs of increasing duration.
    - Demonstrate ability to operate continuously for 100 hours.
    - Achieve plant availability of 80 percent over first year of operation.
    - Install and evaluate corrosion coupons of typical component material (e.g. various stainless and carbon steels).
    - Periodically inspect critical plant subsystems for wear or damage.
- **Off-Design Operations:**
    - Following a year of normal operations, operate combustor under off-design conditions to establish a basis for acceptable operating limits.
    - Return plant to steady-state operations following completion of off-design performance tests.

Results of Testing and Operations

- **System/Plant Commissioning**
    - CES successfully renovated and calibrated existing power plant subsystems.
    - Several new plant subsystems (O_2, NG, condenser) failed to achieve full specification performance, but capabilities were sufficient to permit satisfactory GG operations.
    - CES commissioned the GG with no limiting factors.
- **Normal Steady-State Operations**
    - The unique technology being demonstrated, the GG, operated over a period of more than a year with no significant anomalies. The GG demonstrated more than 100 hours of continuous operations, surpassed 1,300 total operating hours in nine months of operations, and achieved over 95 percent availability.
    - Corrosion coupons were installed in two locations and exposed to drive gases for 500 operating hours. As expected, stainless steel coupons showed few effects while carbon steels exhibited extensive corrosion.
    - GG-induced system outages were rare. When they occurred, they were primarily caused by seal or fitting leaks, which have been corrected with more durable materials.
    - Off-the-shelf plant subsystems unrelated to the GG were more problematic. Significant reliability problems surfacing for both O_2 and NG compressor systems.
- **Off-Design Operations**
    - CES conducted off-design operations periodically in conjunction with steady-state operations.
    - The combustor performed well through significant variations in excess O_2, water-fuel ratios, and operating temperature.
    - High water-fuel ratios were found to significantly increased CO and NOx emissions, but GG operation remained stable and reliable.

Conclusions

- The reliability of the GG was excellent. It was easy to start and easy to control. GG operations were stable over a broad range of operating parameters, including wide variations in excess oxygen, operating temperatures, and power levels.
- The sole weak areas were seal leaks at spool interfaces and water injection fittings. These have been corrected by changing to different types of seals.
- Though the GG is operable and stable over a wide range of parameters, drive gas residence times, combustion temperatures, and the amount of excess oxygen directly affected CO and NOx emissions. NOx and CO emissions vary in opposite directions as the operating parameters are changed.
- CO and NOx emissions were low. CO emissions are reduced when fingered diluent injectors are used in lieu of edge-spray injectors. CES believes that the use of fingered diluent injectors and further "tuning" can reduce emissions substantially—to below one part per million by volume, corrected to 15% O_2 (for comparison with gas turbine-

powered systems). These low emissions levels were reached without any exhaust clean-up system, such selective catalytic reduction (SCR).

Recommendations

- Conduct additional GG testing to evaluate combustion control strategies to further reduce NOx and CO formation.
    - Status —Follow-on GG testing is scheduled for Fall 2006 to define GG operating parameters (e.g., water-fuel-O_2 ratios, combustion temperatures) that will minimize NOx and CO emissions.
- Conduct GG demonstration testing with coal-derived synthetic gas (syngas) to validate combustor compatibility with various syngas heating values and particulate contamination. Operational flexibility of the GG in its ability to use syngas of relatively low heating value and varied composition allows the CES system to use gasified solid hydrocarbon fuels, such as coal, petcoke, and biomass as well as renewable fuels, such as biogas and landfill gas.
    - Status—In September 2005, DOE awarded a contract to CES to develop a preliminary design concept for a commercial-scale, syngas-fueled oxy-combustor. The CES syngas combustor work is being conducted in parallel with a DOE-Siemens contract to develop a compatible high temperature (3,000°F) steam turbine. During Phase I, CES is gathering operational data with the existing KPP GG by operating it with *simulated* syngas, which is produced by blending component gases from tube trailers (testing on-going during May-June 2006). CES will conduct additional GG syngas testing in the third quarter of 2006 with a new main injector specifically designed to accommodate the oxy-fuel ratios appropriate for stoichiometric combustion of syngas.
- Conduct GG compatibility testing with gas turbines, with the goal of applying CES technology to ultra-low emission peaker power plants. Using the power turbine portion ("hot section") of a gas turbine, rather than a steam turbine, improves system efficiency because the GG can be operated at higher temperature. CES has initiated an effort to adapt a J79 gas turbine, a retired military aircraft engine, to be powered by the GG for peaker plant applications.
    - Status—CES is preparing a formal Design Book on CES-cycle peaker power plant configurations at the request of southern California utilities. In addition, in January 2006, CES began design modifications to an off-the-shelf J79 power turbine to permit its use in ultra-low emission, low capital cost peaker plants.

Benefits to California

- The Kimberlina natural gas-fired, near-zero emission power plant demonstrated exceptional reliability and maintainability of the CES GG throughout its test period.
- Operations at KPP demonstrated that a natural gas-fired power plant operating in an open cycle mode (exhaust vented to the atmosphere), such as in a peaker power plant,

and <u>without</u> using emissions control technologies such as SCR, can reduce emissions of criteria pollutants by a factor of 2-3 below current Best Available Control Technology (BACT) standards. Future combustor and control system improvements are expected to reduce GG emissions by an order of magnitude below existing BACT standards.

- **When the CES GG is operated in the normal closed cycle mode, as in a Zero-Emissions Power Plant, all exhaust gases (primarily CO_2) are captured, CO_2 is sequestered or used for industrial purposes, and power plant emissions drop to virtually zero. Used in this way, the CES cycle is a "climate neutral" electricity generation technology.**
- CES demonstrated that its combustion technology provides an efficient, economic process for capturing CO_2 emissions from power plants and thereby eliminating this source of greenhouse gas emissions. Once captured, the CO_2 can be sequestered, or sold for commercial purposes such as enhanced hydrocarbon recovery.
- Successful testing at KPP resulted in the insurance industry providing full commercial insurance coverage for the CES gas generator. This was not available at the outset, and directly resulted from this CEC-funded demonstration program. Insurability of equipment is key to subsequent commercial deployment.
- The CES combustor is capable of near-zero-emission operations with any carbon-based gaseous fuel over a wide range of operating powers and conditions. Fuels suitable for use with the CES combustor include landfill gas, anaerobic digester gas, and synthetic gases from gasified solid carbonaceous fuels (e.g., biomass, coal, and petcoke). The former are abundantly available in California's landfills and agricultural industry. The latter can be found within agriculture and industrial applications.
- The CES technology has now been demonstrated to be ready for use in:
  1. Base-load, zero-emission power plants, with optional carbon capture
  2. Ultra clean peaker power plants (venting drive gases to atmosphere)
  3. Integrated power production and
     - gasification of liquefied natural gas
     - thermal desalination, or
     - enhanced hydrocarbon recovery (oil, natural gas, coal bed methane).

  Although any of the foregoing applications would justify the Energy Commission's investment in the Kimberlina demonstration, the matrix of capabilities of the CES cycle enables this technology to offer an extraordinary opportunity to simultaneously improve California's future energy supply, economy, and environment.
- In the near term, ultra low emissions, affordable, CES peaker power plants will be available to help stabilize California's peak energy demand. CES is actively pursuing deployment of the first of these modular peaker units in Southern California, where such power is most needed.

- Base-load power plants using CES technology and incorporating CO_2 capture will likely be first demonstrated in 50 MW_e plants located in The Netherlands and Norway in the 2008-2010 timeframe. When located in California markets, these zero-emission power plants are expected to not only produce abundant clean electrical power, but also provide large quantities of compressed CO_2 for enhanced oil recovery (EOR). According to U.S. Department of Energy studies, CO_2 injection can recover more than five billion barrels of oil from existing California oil fields.
- The CES cycle is also exceptionally well suited for gasifying liquefied natural gas (LNG). A CES combustor could vaporize LNG while also providing exportable electrical power, high-pressure CO_2, and pressurized N_2.
- Waste heat rejected from the CES-cycle can be used for thermal desalination of water in coastal areas that need new sources of potable water.
- The flexibility of the CES-cycle enables it to deliver the promise of clean power through a variety of means—base-load, peakers, EOR—and meet the expanding energy needs of California's citizens.

1.0 Introduction

1.1 Background and Overview

In 1999, Clean Energy Systems, Inc. (CES) submitted a proposal to the Energy Innovations Small Grant (EISG) program of the California Energy Commission's Public Interest Energy Research (PIER) program. The proposal identified the founders of CES, a small Sacramento-area company, as former rocket engine engineers at Aerojet, who envisioned a zero-emissions oxy-fuel combustion system that would drive a turbine and generator to generate electricity at a power plant scale. The proposal requested $74,871 to support development and proof-of-concept testing of a bench scale, 110 kilowatt thermal (kW_t) *gas generator* (GG), the novel CES combustor. The concept involved burning natural gas (NG) in pure oxygen (O_2). With no nitrogen present, there would be no formation of nitrogen oxides (NOx), and with a stoichiometric ratio of O_2 and NG, the exhaust gas would be pure steam and carbon dioxide (CO_2). The Energy Commission funded the project through EISG Grant No. 99-20. By May 2001, CES had successfully manufactured, operated, and completed testing of the bench scale GG.

Overlapping the EISG project, the U.S. Department of Energy's Vision 21 program match funded CES to design, manufacture, and test a 20 MW_t (~10MW_e) GG. With the DOE project well underway, CES submitted a proposal to the Energy Commission in response to a PIER Environmentally-Preferred Advanced Generation solicitation. This project would demonstrate the durability and reliability of the GG and the "CES power cycle" in a small, zero-emission power plant. In February 2002, the Energy Commission awarded CES a contract for the project described in this report. The contract was for $2,003,286 to co-fund the design, construction, and operation of a skid-mounted, 500 kW_e natural gas-fired, zero-emission power plant. This small-scale power plant would be co-located with a conventional power plant in Antioch, California, and utilized to demonstrate the durability and reliability of the CES gas generator (GG) under real-world operating conditions. The demonstration would establish GG performance characteristics, set GG operating limits, and capture the CO_2 generated in the combustion process. CES planned to sell the captured CO_2 for commercial use. Following a two-year GG demonstration, the power plant would be dismantled and removed from the site.

During detailed design of the GG and equipment layout for the zero-emission demonstration plant, the power company contributing the Antioch demonstration site notified CES that site availability faced significant delays. To preclude schedule delays, CES immediately sought an alternative test location. After an extensive review of power plant sites in the Sacramento and San Joaquin Valleys, CES located an idle 5.5 MW_e biomass power plant (Kimberlina power plant [KPP]; see Figure ES-2.) near Bakersfield, California. Although an order of magnitude larger in size than the Antioch design, KPP was ideal for completing the GG durability test with no conflicting demands for cooling water or natural gas. CES recommended, and the Energy Commission approved, relocation of the demonstration from Antioch to the Bakersfield plant. CES purchased KPP in 2003 and began immediate facility renovations. In 2004, the Energy Commission committed an additional $2,000,000 to co-fund the expanded scale of GG testing.

CES installed new equipment to meet GG operating requirements including high-pressure O_2, NG, and feed water supply systems, a geothermal-type condenser, and a liquid ring vacuum pump. CES took advantage of KPP's larger turbo-generator capacity to use the DOE 20 MW_t GG-design, operating it at 16.8 MW_t (5 MW_e), in lieu of the planned 500 kW_e unit. However, because of the ten-fold increase in demonstration scale (from 0.5 to 5 MW) and attendant capital cost increases, CES recommended that CO_2 treatment and sequestration be removed from project scope. The Energy Commission concurred, and CO_2 sequestration was deferred to a future phase, outside the scope of the PIER project.

1.2 CES Power Cycle

In the CES power cycle, oxygen is combusted with clean, gaseous fuels composed of the elements carbon, hydrogen, and oxygen (Figure 1). Acceptable fuels include natural gas; synthetic gas derived from coal, refinery residues, or biomass; landfill gas; and anaerobic biodigester gases. Combustion is maintained at near-stoichiometric conditions, with temperature controlled by injection of de-ionized (DI) water through the GG's main injector and GG cool down segments (Figure 2). The resultant drive gas, a high temperature/ high pressure steam-CO_2 mixture, is directed through multi-stage turbines to drive an electrical generator. The drive gas may be reheated between turbine stages by an oxy-fuel reheater for improved plant efficiency. As the drive gas exits the final turbine stage, it passes through a heat exchanger to capture residual heat, and is then directed to a geothermal-type condenser.

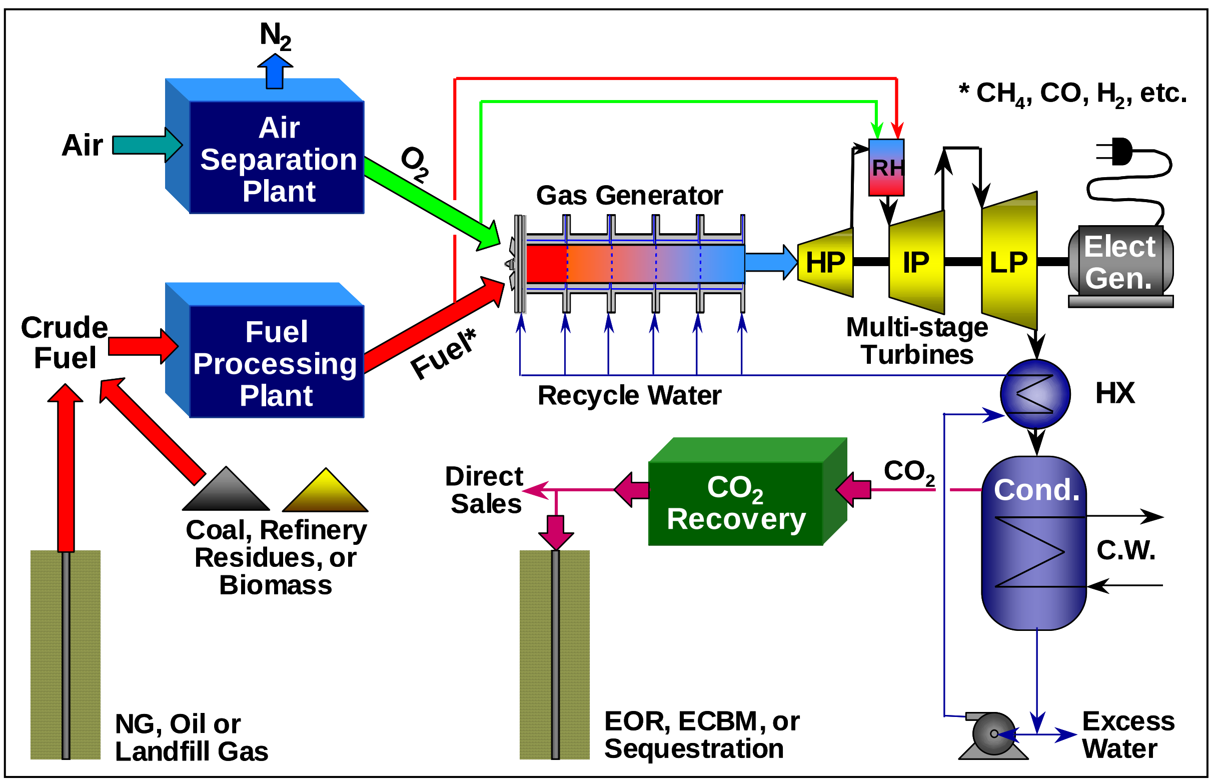


Figure 1. CES Power Cycle Process Diagram

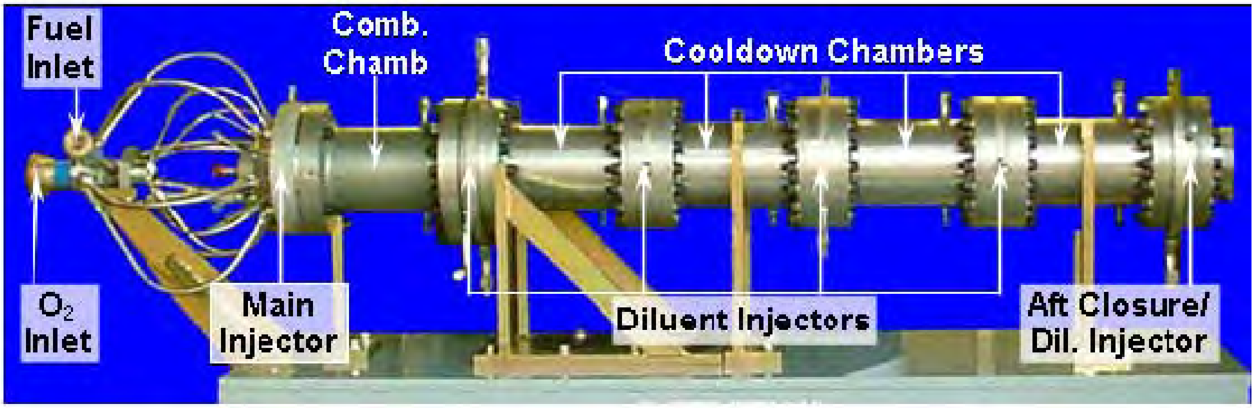


Figure 2. CES gas generator (GG); length is about 9 feet.

In the condenser, the drive gas is cooled, separating into its components, water and CO_2. The CO_2 is extracted by a liquid ring vacuum pump and processed by a CO_2 recovery system. The processed CO_2 can be sold, injected for enhanced oil recovery, used for coal-bed methane recovery, or sequestered in subterranean formations. Most of the water is recycled to the gas generator but excess high-purity water is produced and available for export.

1.3 Project Objectives

The project objective was demonstration of the durability and reliability of a near-zero emission, gas-fired power plant utilizing CES combustor technology. The CES GG and digital control system would operate in a full-up power plant for an extended period to obtain reliability and durability data. Testing would nominally include one year of normal steady-state operations and a second year of combined off-design and steady-state operations. The GG was expected to accumulate more than 1,000 hours of combustor operating time. Specific objectives included:

1.3.1 Plant commissioning

- Install CES combustor and control system.
- Renovate, calibrate, and repair existing KPP subsystems.
- Add high-pressure O_2, NG, and DI water subsystems.
- Replace existing steam turbine condenser with a geothermal-type unit; add liquid ring vacuum pump
- Upgrade plant safety and security systems to current standards.
- Operationally test, and formally commission, each subsystem.

1.3.2 Normal steady-state operations:

- Operate GG and plant subsystems in long duration runs.
    - o Operate under steady-state conditions of temperature, pressure, and power level with automatic upward and downward cascading of power level to set-point values.
    - o Maximize the number of starts, operating hours, and sustained runs (100-hour goal).

- Measure radial temperature distribution of gases within the GG and evaluate strategies for improving the radial temperature profile.
    - Determine the effects of diluent water injection methodology on drive gas composition and radial temperature profile at the GG exit.
    - Measure condensate quality.
    - Adjust/refine control system.
    - Prepare operating data log.
    - Prepare GG maintenance log.
- Achieve plant availability of 80 percent in first year of operations.
- Install and evaluate corrosion coupons of typical component material (e.g. various stainless and carbon steels).
- Periodically inspect critical plant subsystems for wear or damage.
- Prepare First Year Operating Data Report.

1.3.3 Off-design operations

- Following a year of normal operations, operate combustor under off-design conditions to establish a basis for acceptable operating limits. Return plant to steady-state operations following completion of off-design performance tests.
- Prepare Off-Design Performance Report.

1.4 Report Organization

The report is organized as follows:

- Introduction (Section 1.0)—provides project background and detailed objectives (durability and reliability demonstration) of the CES GG.
- Approach (Section 2.0)—provides technical approach taken by CES to accomplish each objective.
- Results (Section 3.0)—presents outcome of each project objective addressed in the technical approach.
- Conclusions (Section 4.0)—presents conclusions derived from the results of each approach; presents project's commercialization potential; presents specific recommendations for future research; and presents California benefits resulting from this contract.
- References (Section 5.0)—lists documents cited in the body of the report.
- Glossary (Section 6.0)—defines each acronym used in the report.
- Appendices (Section 7.0)

2. Project Approach

2.1 Commission Kimberlina Power Plant Subsystems

Prior to beginning testing of the CES GG, the moth-balled KPP was reactivated and returned to operational status. The entire power plant was surveyed and each subsystem evaluated for applicability, condition, and compliance with current codes. Each plant subsystem was rebuilt, replaced, or (if not needed) decommissioned-in-place.

2.1.1 Update existing KPP subsystems

The following plant subsystems were inspected, repaired or replaced, and re-commissioned preparatory to conducting GG testing:

- **Domestic water system**—Domestic water piping was inspected and repaired as required. All plant sinks and bathrooms were rehabilitated. Bottled water systems were provided for drinking purposes.
- **Fire protection system**—Piping for the fire protection system was inspected and defective piping replaced. New shut-off and flow-sensing valves (the latter wired to the fire department) were installed and all sprinkler heads inspected. New hoses were installed at all six local fire fighting stations, and new fire extinguishers placed in 11 extinguisher stations around the plant. Staring array, ultra-violet/infrared fire sensors were installed to monitor the GG, NG compressor, and O_2 skid.
- **Steam turbo-generator**—Thorough inspection and testing was completed on the KPP steam turbo-generator (STG). The steam turbine, connecting gearbox, and generator were inspected, serviced, and tested with only minor discrepancies noted. The STG's Bently-Nevada vibration and temperature monitoring system was found to be operational and in good repair. Spin testing confirmed that the STG was well balanced and that STG controls/lube oil system worked well.
- **Service and control air system**—Three of the four KPP control air compressors were rehabilitated and brought on-line to provide high pressure air for KPP. The fourth compressor was decommissioned-in-place. A new air filter/dryer was purchased and installed adjacent to the main compressor bank to provide clean, filtered air to KPP control systems.
- **Cooling water system**—All cooling water system piping to and from the Marley Two-Cell Cooling Tower was mechanically cleaned via hydro-blasting to remove rust and scale. Affected piping included main distribution piping, piping within the cooling tower, and cooling water piping to the STG air and oil coolers. Both main and auxiliary cooling pumps were removed and rebuilt, including their electric motors. The cooling tower was inspected and cleaned, including changing the motor oil for both cooling tower fans.
- **Lighting system**—Most interior sodium and mercury vapor lighting was in a poor state of repair. It was replaced by metal hydride units which significantly improved average foot-lambert illumination within the plant. Hazardous duty lights were added for the

GG and oxygen skid. All battery-operated emergency lighting fixtures were replaced with new units and batteries. Exterior perimeter lighting was reactivated following trouble-shooting and repair.

- **Security system**—Plant security was upgraded to improve access control. Improvements included new fencing to segregate the oxygen and GG systems; automated plant gate operation; installation of a multi-camera plant monitoring system; installation of crash doors in the boiler building; and addition of remote-sensing intrusion and fire protection systems. The latter includes flow sensors for the KPP fire sprinkler system and detection sensors for both fire and leaking NG/O_2.

2.1.2 Addition of new KPP subsystems

Facilitation of KPP for GG operations required the addition of subsystems not included in the original plant. The following subsystems were installed and commissioned preparatory to conducting GG testing:

- **Feed water system**—The existing feed water system was removed due to material and pressure incompatibilities. A new feed water system was installed consisting of: a high-pressure (1,800 psig) stainless steel feed water pump; a 1,000 gallon poly feed tank; two stainless steel, 1 micron (μ) filters; a stainless steel pressure control valve, and a plant control system. In addition, all feed water piping was replaced with chlorinated polyvinyl chloride (CPVC) (low pressure applications) and stainless steel (high pressure applications). Existing make-up pumps were retained to transfer DI water between the large (7,000 gal) storage tank and the small (1,000 gal) feed tank via recirculation lines.
- **Natural gas system**—A high-pressure (1,600 psig) two-stage gas compressor was installed to provide NG to the GG skid. Pressure control and relief valves were provided for supply line modulation and a 0.3 μ filter incorporated.
- **Oxygen system**—A complete oxygen system was added adjacent to the KPP boiler building. It consisted of an 11,000 gallon cryogenic liquid oxygen (LOX) storage tank, a triplex high-pressure cryogenic pump, a LOX vaporizer, three accumulators, two 10μ filters, and pressure control/ relief valves. It also included a stand-alone, programmable logic controller to control the start/restart of the cryogenic pump. All critical components were constructed of oxygen-compatible materials (i.e., Monel, stainless steel, brass, chlorotrifluoroethylene [CTFE], and virgin polyetherether ketone [PEEK]).
- **Condensate system**—The CES cycle creates CO_2 which, when it goes into solution with DI water, makes GG feed water slightly acidic. Consequently, CES replaced all condensate system components touching the condensate stream (the "wetted" areas) with non-corrosive materials. Carbon steel piping was replaced with stainless steel and CPVC and the condensate pump's carbon steel head was replaced with a stainless steel head. In addition, a simplified feed water polishing system was incorporated, a stainless steel after-cooler emplaced (to reduce condensate temperature faced by the polishing system resin beds), and two stainless steel 1μ filters added.
- **Package boiler**—An Ajax package boiler system was added to supply gland seal steam for the STG and also to provide steam to pre-warm steam piping and the STG. Fulton

centrifugal pumps were utilized to provide de-aerated (CO_2-free) DI water from the KPP DI water system for the package boiler.

- **Condenser system**—A new stainless steel, geothermal-type condenser was installed to handle the low pH condensate and the (relatively) high volume of non-condensable gases exiting the STG. While a typical condenser sees less than 0.002 percent non-condensable gases, the CES drive gas contains approximately 10 percent. Geothermal condensers contain interior baffling to promote efficient separation of non-condensable gases (primarily CO_2 in the CES cycle) from the steam condensate. In addition, a liquid ring vacuum pump (LRVP) was added to remove CO_2 from the condenser and also lower internal condenser pressure to the 20 inches of mercury vacuum needed for efficient steam turbine operation. The LRVP vents extracted CO_2 to atmosphere via a high stack. Budget constraints deferred CO_2 processing and compression for injection into gas and oil fields (for enhanced oil recovery) to a future phase, outside the scope of this project.
- **Feed water polishing system**—A simple, double resin-bed system replaced the complex water polishing system previously used at KPP. The new system's primary purpose is now limited to providing feed water protection against "break through" leakage from condenser cooling water. Its resins are regenerated off-site on an "as needed" basis. An "after cooler" permits use of less-expensive resins by limiting feed water temperature to a maximum of 110°F. The former polishing system was decommissioned and left in place.

2.1.3 Decommission of unneeded KPP subsystems

Several KPP subsystems were either completely outdated or had no use in the CES cycle. Consequently, they were removed or decommissioned "in-place" preparatory to conducting GG operations at KPP.

- **Existing boiler**—Decommissioned in-place (no further utility—to be removed).
- **Existing boiler feed pump**—Replaced with new unit (original unit unable to meet pressure requirements and pump material was incompatible with acidic condensate).
- **Existing condenser**—Replaced with geothermal-type unit (original unable to handle non-condensable gases, condenser material incompatible with acidic condensate).
- **Existing condensate system**—All elements replaced except condensate pump motor (material incompatibility with acidic condensate).
- **Existing condensate treatment system**— Decommissioned in-place (complex treatment system no longer needed to treat a steady stream of low quality boiler make-up water—the CES cycle produces a steady stream of high quality water which, in the closed CES cycle, exceeds GG make-up water requirements).
- **Existing material handling system**— Decommissioned in-place (solid materials not combusted in modified power plant).

2.2 Commission Gas Generator

Prior to beginning long-term durability testing, the GG and its digital control system were installed at KPP and subjected to extensive testing. Following test completion, the GG and its control system were commissioned.

2.2.1 Install gas generator

The GG was installed on a concrete pad adjacent to the existing KPP biomass boiler and the GG digital control system (DCS) was installed in the power plant's control room. Concurrent with installation of GG utilities—electrical power, control instrumentation, and instrument air—safety systems were installed. The latter included ultraviolet/infrared fire detectors, evacuation alarms (warning lights and public address system), personnel security fencing, crash bars on emergency exit doors, O_2 and NG leak detectors, emergency lighting, exhaust hood/fan, explosion-proof lighting over the GG, and video surveillance cameras.

Five plant subsystems connect directly to the GG**:** NG, O_2, feed water, instrument air, and purge gas. The commodity subsystems (NG, O_2, feed water) were connected to the GG skid as individual subsystems and then commissioned. The feed water system was utilized to conduct "cold flow" testing of GG water injection and cooling circuits. Cold flow testing of GG fuel circuits initially used bottled methane. It was then switched to NG supplied by the NG compressor. CES conducted preliminary "cold flow" testing of the GG igniter and main oxidizer circuits utilizing high-pressure nitrogen (N_2) from tube trailers. Cold flow testing with O_2 was conducted using the O_2 skid. The GG was then connected to steam lines routed to both the by-pass stack and STG.

The pre-assembled GG DCS was installed in KPP's second floor control room. Electrical power was hard-wired to the DCS main power supply and signal wiring was run to the GG skid in the plant's former boiler room. Existing DCS data acquisition provisions were expanded and modified to accommodate KPP legacy systems. To ease the DCS integration workload with legacy analog systems, CES developed an Integration Controller (IC) to accept signals from existing plant control and sensor systems, integrate them, and then provide them in a digital format to the DCS. Programmable logic controllers similar to those used in the DCS were used to provide standardized, high-speed computational capabilities.

2.2.2 Commission gas generator

Formal GG commissioning was performed in a stepwise fashion, beginning with igniter circuits, and then moving on to valve timing and low fire conditions.

- **Igniter**—Cold flow tests were performed and adjustments made to capillary length (O_2, NG, N_2, and argon circuits). All mixture ratios were validated as being within design values.
- **Diluent injector circuits**—Cold flow tests confirmed the hydraulic characteristics of the GG circuits and were used to establish desired/predicted GG operating parameters. They also established appropriate "stop" positions of diluent injector valves for low-fire.

- **Igniter valve timing**—Igniter valve timing tests were performed on the igniter NG, O_2 core, and O_2 coolant valves, defining valve lead-time from signal initiation to an opened and closed valve. Data analysis also verified repeatability of these response times.
- **Diluent injector valve timing**—GG cold flow tests defined the hydraulic characteristics of the GG circuits which were then used to establish desired/predicted GG operating parameters. They also established appropriate "stop" positions of diluent injector valves for low-fire conditions.
- **Low- to high-fire tests**—The GG was then moved through a series of gradually more complex verification and integration testing: igniter sequence tests, short duration igniter tests, short-duration low-fire tests, longer-duration low-fire tests, and higher power GG operations, including synchronization. Once start sequences were validated, run lengths and power levels were gradually increased, with power changes controlled by use of the "ramping" algorithms in the DCS.

2.3 Normal Steady-State Operations

KPP was nominally operated under normal steady-state conditions of temperature, pressure, and power level. Periodically, the GG was operated under off-design conditions to establish and document operating limits and then returned to normal steady-state conditions. During both states, power level was automatically controlled via upward and downward cascading of power to set-point values. Typical plant and GG start sequence follows.

2.3.1 Plant startup

Prior to GG start up, a complete maintenance check is performed on all plant subsystems and required pre-start maintenance activities are performed. Once subsystems are ready for operation, the STG and steam lines are pre-warmed by the auxiliary package boiler. After the STG and steam lines reach a minimum operating temperature, GG drive gas can be introduced.

The GG is started by the DCS via an automatic sequence mode. Within a few seconds after start initiation, the GG is operating in a stable mode and generating drive gas at low-fire (20 percent power). Because of the rapid rise in drive gas temperature and pressure exceeds STG rate-of-change limitations, drive gas is initially discharged to atmosphere via the plant by-pass exhaust stack.

Drive gas pressure in the GG and steam lines is maintained at the operator-selected Pressure Set Point (PSP) by the DCS. Once stable GG operation is confirmed, a portion of the drive gas is diverted to the STG. Approximately five percent GG power will synchronize the STG with the local electrical grid, provided the turbine condenser is operating in its sub-atmospheric condensing (design) mode (LRVP on line).

Once the STG has been synchronized with the electrical grid, STG controls are placed in the "Inlet Steam Pressure" control mode. Drive gas flow is gradually directed from the exhaust stack to the STG by the DCS and then STG begins generating electrical energy. Once all GG drive gas has been directed to the STG, the PSP on the STG by-pass valves (to the exhaust stack) is reset higher than the PSP at the STG controller. All GG drive gas will continue to be directed to the STG unless the STG suddenly trips or otherwise shuts down. At that point, the STG by-pass valves act as automatic relief valves and release rejected drive gas flow through the exhaust stack.

With the STG running in "Inlet pressure Control" mode, additional electrical power is produced by increasing GG output. The DCS provides additional GG power by modulating GG feed valves to a more open position. The DCS provides drive gas temperature, pressure, and flow rates as needed by the STG. The DCS/STG controls algorithm minimizes thermal metal stress, prolonging the life expectancy of power plant equipment.

2.3.2 Operate GG under normal steady-state conditions

Following start up, the GG was operated in a normal band of temperature, pressure, water-fuel ratio, and excess O_2. Initial operations confirmed GG and plant subsystem start up, shut down, and operating parameters, reliability, and repeatability. Following an initial series of GG runs, GG and subsystem operating parameters were adjusted for optimal operation. To reduce the number of manual operator adjustments required to balance subsystem outputs, additional human-machine interface (HMI) linkages were added between the subsystem controllers and GG DCS/IC programmable logic controllers. This added system integration improved operator awareness of system excursions outside designated parameters, permitted earlier operator intervention to correct operating conditions, and increased the automation of normal GG-subsystem feedback.

Following a series of initial shakedown runs, GG run time durations were gradually increased until 100 hours of continuous, uninterrupted operation had been demonstrated. Weekly GG and support subsystem run times typically ranged from 20 to 50 hours, with a maximum of 113 hours logged. The primary constraint on long duration GG runs was the reliability of plant support subsystems—until support system teething problems were resolved, the GG seldom accumulated 24 hours of continuous operations before a support systems faulted, forcing the operator to reduce GG power or shut down. An unanticipated benefit of the shorter run times, however, was a dramatic increase in total system start ups to 190 within the first nine months of long duration testing (315 total starts). As the power industry ranks start up and shut down as one of the most demanding elements of power plant operations, this high total of successful GG start ups was a convincing display of GG durability and reliability.

GG operating power levels—and electrical export to the grid—gradually increased with operating experience. With a nominal GG thermal output of 16.8 MW_t, CES achieved a maximum sustainable GG power output of 60 percent (1.9 MW_e), with a peak GG power output of 76-80 percent (2.5 MW_e). Full GG power was not achieved due to subsystem capacity limitations in the NG compressor and condenser. The NG compressor delivered only 90-95 percent of its specification NG requirement and the condenser/liquid ring vacuum pump could not maintain its required condenser pressure (10 inches Hg) above 70-75 percent of specified turbine exhaust flow. These shortcomings were intrinsic to the as-built design of the NG compressor, condenser, and liquid ring vacuum pump. Replacement of the non-conforming components would have delayed the Kimberlina test program by six or more months. However, Kimberlina test objectives could be successfully completed at lower GG power levels, so CES elected to conduct the test program within the above capacity limitations. An additional operating limitation occasionally arose with the O_2 system. During periods of low temperature and high humidity, the LOX vaporizer would ice up at high GG power levels (high O_2 flow) and the temperature of delivered gaseous O_2 would gradually drop until a temperature "kill" limit was reached for the GG. CES overcame this problem by de-icing the vaporizer with a fire hose and this winter-time limitation had little effect on GG operations.

KPP initially operated a single shift, eight hours/day schedule until the plant was commissioned. In July 2005, KPP moved to a 14-hour, two-shift/day operation for the first six months of long duration testing. In January 2006, single-shift operations were resumed (eight hours/day, five days/week). CES elected not to routinely run 24 hours/day to minimize added personnel costs.

2.4 Off-Design Operations

The GG was periodically operated under off-design parameters following the first three months of durability runs. The purpose of the off-design parameter testing was to demonstrate stable combustor operations during less-than-ideal operating conditions, define the range of acceptable operating conditions, and determine the impact on performance (power, temperature, emissions) of off-design operating conditions. After each series of runs using off-design parameters, the GG was returned to normal operations. During the off-design runs, the GG was operated under varying excursions in excess O_2 (2-10 percent), water-O_2 ratios (1.2 to 1.4), and drive gas temperatures (450°F to 700°F, the latter being the upper limit of STG operations).

The basic premise of the CES-cycle is that combustion under balanced stoichiometric conditions will produce a minimum of unwanted by-products (i.e., pollutants). However, since the reactants in a given combustion environment are never perfectly distributed (mixed), CES uses a slight excess of O_2 to improve the likelihood of complete combustion and minimize the formation of undesired by-products.

Excess O_2 was varied from 2 to 10 percent to examine its impact on the creation of undesirable products—mainly CO and NOx—and determine optimal excess O_2 percentages which minimized these products. Two percent was selected as the minimum value needed to ensure complete combustion. The upper boundary (10 percent) was selected as the maximum "reasonable" amount which could affect CO, NOx, and hydrocarbon output.

Water-O_2 ratios were selected to examine the interrelationship of water injection to O_2 (at any given excess O_2 level) in the formation of CO and NOx. Ratios were restricted from 1.2 to 1.4 to keep the amount of water entering the system in the proper amount needed to maintain the desired combustion temperature range.

Drive gas temperature was measured at the exit of the GG. Although the combustor was designed to operate at drive gas temperatures up to 1,500°F, steam turbine operating parameters limited the maximum off-design temperature set point to 700°F. A low temperature set point of 450°F was selected to provide a significant statistical range with a high enough temperature to ensure that the steam remained superheated entering the turbine.

3.0 Project Results

3.1 Gas Generator and Digital Control System Commissioning

Prior to undertaking long-term durability testing, the gas generator and its digital control system were subjected to numerous tests of various types. The early tests insured that the system was ready for turnover for routine operation. Subsequently, further tests were conducted to fully commission it for long-term durability tests. A summary listing of the commissioning tests on the GG under this contract is shown in Table 1 and a log of all the test runs performed at the Kimberlina Power Plant since 16 December 2004 is presented in Appendix A. In Table 1, Test Plan Items 5.1.1 through most of 5.3.1.3 were early tests that included leak tests of the GG system, igniter and GG cold flow tests, igniter and GG valve timing tests, igniter sequencing tests, short-duration igniter tests, GG low-fire sequencing tests, short duration GG low-fire tests, longer duration GG low-fire tests (Appendix A, Runs 1-5) and lastly, a higher power, long duration hot-fire test (Appendix A, Run 6).

Commissioning of the Kimberlina Power Plant was accomplished in Test Plan Items 5.1.1 through 5.3.2.4 (Table 1). That testing encompassed igniter tests, GG low-fire testing, high-fire operation of the GG while exhausting to the stack, and high-fire operation of the GG while driving the turbine. The igniter tests (Test Plan Items 5.1.1-5.1.6) were performed during the period from early September through 4 December 2004. The GG low-fire testing (Test Plan Items 5.2.1—5.2.7) was performed during the period from early September through 21 December 2004 and included test Runs 1-5 and part of Run 6 (Appendix A). High-fire operation of the GG (Test Plan Items 5.3.1.1—5.3.2.4) was performed during the period from 21 December 2004 through 6 June 2005, encompassing Runs 6 through 131. Those tests involved 125 successful starts and about 237 hours of GG operation at power levels up to ~90% of design based on fuel flow rate as measured by the flow meter on the GG. Subsequent checks of the GG fuel flow meter against the gas supply company's gas meter indicated the GG flow meter to be indicating only about 85% of that of the supplier's meter. Thus, power outputs as given throughout this report may be lower than actual by about 15%.

Table 1. Summary List of Gas Generator Tests

Com-ponent	Test	Comment	Test Plan
Igniter	Static proof	Requires proof/ leak fixture	5.1.1
	Leak check	Requires proof/ leak fixture	5.1.2
	Cold flow	Performed on integrated GG system	5.1.3
	Valve timing	Performed on integrated GG system	5.1.4
	Igniter sequencing	Performed on integrated GG system	5.1.5
	Ignition tests	Performed on integrated GG system	5.1.6
Gas Generator (Low-Fire Op.)	Static proof	Requires proof/ leak fixture	5.2.1
	Leak check	Performed on integrated GG system	5.2.2
	Cold flow	Performed on integrated GG system	5.2.3
	Valve timing	Performed on integrated GG system	5.2.4
	Low-fire sequencing	Performed on integrated GG system	5.2.5
	Short-duration low-fire	Performed on integrated GG system	5.2.6
	Extended-duration low-fire	Performed on integrated GG system	5.2.7
Gas Generator (High-Fire Op. Exhausting to Stack)	Manual power ramping	Performed on integrated GG system	5.3.1.1
	Cascade power ramp w/manual P &T controls	Performed on integrated GG system	5.3.1.2
	Auto. Power ramp w/auto. P & T controls	Performed on integrated GG system	5.3.1.3
	As above w/manual XS O_2 control	Performed on integrated GG system	5.3.1.4
	As above w/auto. XS O_2 control	Performed on integrated GG system	5.3.1.5
Gas Generator (High-Fire Op. and Drive Turbine)	Switch Drive Gases to Turbine & Produce Electricity	Performed on integrated GG system	5.3.2.1
	GG Power-Command Op. & Prod. Elec.	Performed on integrated GG system	5.3.2.2
	Operate in Elec.-Power-Following Mode	Performed on integrated GG system	5.3.2.3
	Emergency GG Shutdown	Performed on integrated GG system	5.3.2.4
Long-Term Durability Testing	First year steady-state operations	Performed on integrated GG system	7.1.1
	First-year off-design operations	Performed on integrated GG system	7.1.2
	Second year operations	Performed on integrated GG system	7.2

The long-term durability tests identified as Items 7.1.1-7.2 in the Test Plan (Table 1) generally encompass the period from 28 February 2005, the first export of power to the grid, through 24 April 2006 and test numbers 31 through 410 (Appendix A).

3.1.1 Power ramping and steady-state operations

During the first year of operation, the GG was tested under high-fire conditions in both power-ramp and steady-state high power operating modes. In each test the GG was started in a low-fire operating mode (~20% power level) using the by-pass O_2, fuel, and water injection circuits via their respective ON/OFF valves. Following low-fire startup, the modulating flow control valves in the main O_2, main fuel, main injection water, and first, second, and third diluent injection circuits were activated via the DCS to achieve higher power levels. Two series of high-fire tests were conducted. In the first series, the drive gases were directed to the stack via main steam line bypass valves. In the second series, the drive gases were directed to the steam turbo-generator (partially and totally) for grid synchronization and power generation. These test series are described more fully in the following sections.

3.1.1.1 Series 1: High-fire tests exhausting to the by-pass stack

Test Series 1: This test series demonstrated:

1. Manual power ramping to a relatively low gas discharge pressure and temperature;
2. Automatic cascade power ramping with automatic header pressure control and manual header temperature control;
3. Automatic cascade power ramping with automatic header pressure and temperature controls and manual control of excess O_2; and
4. Automatic cascade power ramping with automatic header pressure and temperature controls and automatic control of excess O_2.

3.1.1.1.1 Manual power ramping

Test Plan Item 5.3.1.1: Demonstrate normal low-fire startup with the exhaust stack by-pass valves manually set to achieve desired operating pressure. Manually increase pressure stepwise to 400 psig (or other value) and set DCS to automatically control at 400 psig. After stable low-fire operation is achieved, manually ramp GG power to a mid-range set point. Demonstration is deemed successful if steam header pressure and temperature are controlled during and after the power ramp. Demonstration may be interrupted by automatic trips and deemed successful if trips are due to an improper limit value or an equipment failure outside the GG system.

Test Results: The first manual power ramp in this series (Run 13) was conducted on 17 January 2005. The low-fire condition was maintained for 18.8 minutes during which the operating pressure was manually adjusted stepwise from ~150 psig to 400 psig and then placed in automatic pressure control mode. The power was then manually increased stepwise to ~30% (based on fuel flow rate) while maintaining automatic pressure control. A subsequent manual increase in the O_2 flow rate caused the header temperature to rise to the set limit value of 600°F and an automatic GG shutdown after 20.8 minutes of operation. Automatic pressure control was maintained throughout.

These test results demonstrated that the DCS would properly control the GG under manual control and that the GG would successfully and reliably ramp pressure to the selected pressure and temperature set points.

A second test (Run 14) was performed 18 January 2005. The low-fire condition was maintained for 44.2 minutes during which the operating pressure was manually adjusted stepwise from ~150 psig to 400 psig. Automatic pressure control mode was enabled after 26.7 minutes of GG operation. Power was then manually increased stepwise to ~30% (based on fuel flow rate) while maintaining automatic pressure control. O_2 flow rates and injection water flow rates were also increased stepwise to maintain an approximate stoichiometric O_2/NG ratio and a header temperature below the set limit value. Automatic pressure control was maintained throughout while O_2/NG adjustments were made and header temperature ranged from 435°F to 570°F. The test was automatically shut down after 1.2 hours of operation when a system limit value was reached (no GG or DCS malfunction, simply a limit "trip" that was set too low).

These test results demonstrated that the DCS would automatically adjust pressure to maintain the pressure set point as power output was manually increased and O_2 and temperature were manually adjusted.

3.1.1.1.2 Automatic cascade power ramping, auto pressure control, and manual temperature control

Test Plan Item 5.3.1.2: Demonstrate normal low-fire startup with drive gases by-passed to the stack. Ramp power to prescribed power level at a prescribed rate and hold power level constant. Automatically control steam header pressure. Manually control steam header temperature. Multiple power ramps and hold periods may be conducted during a single demonstration. Demonstrations are deemed successful if the desired automatic power ramps are successfully achieved (pressure under automatic control, temperature manually controllable). Demonstrations may be interrupted by automatic trips and deemed successful if the trips are due to an improper limit value or an equipment failure outside the GG system.

Test Results: The first automatic power ramp demonstration (Run 18) was conducted 3 February 2005. The initial stages of power ramping (from ~20 to 35% power levels) were partially performed by stepwise modulation of one or more of the feed valves. Power level was then ramped in a fully automatic cascade mode from 35 to 40% power at a rate of 3% per minute and held at 40% power for ~10 minutes. Power was subsequently ramped up to 50% power at a similar ramp rate and held at that power level for ~10 minutes. Finally, power was automatically ramped down from 50% power to the low-fire condition (~20% power) at a rate of 3% per minute, held momentarily at the low-fire condition, and the GG was commanded to perform an automatic shutdown. The GG operated at automatically controlled pressures up to 475 psig and produced drive gases at steam header temperatures up to 600°F.

A repeat of this test (Run 19) was conducted on 4 February 2005 with the intent of achieving higher power levels. The results were similar but the test was automatically terminated (tripped) at the 50% power level by a high feed water inlet temperature limit. In this test the GG operated at automatically controlled pressures up to 540 psig and produced drive gases at steam header temperatures up to 660°F.

Two tests (Runs 21 and 22) were conducted on 8 February 2005 with the goal of achieving higher power levels. In the first of those two tests, power was automatically ramped, with intermediate holds at constant power, in the following order of power levels: 30, 35, 40, 50, 60, 70, 65, 60, 55, 50, 60, and 70%. The test was automatically terminated (tripped) at ~74% power level by low NG inlet pressure. In that test, the GG operated at automatically controlled pressures up to 710 psig and produced drive gases at steam header temperatures up to 550°F. In a second test on 8 February 2004, power was similarly automatically ramped upwards, with intermediate holds at constant power, in the following order of power levels: 30, 40, 50, 60, and 70%. It was similarly terminated at 73% power level by a low NG inlet pressure limit. In this second test, the GG operated at automatically controlled pressures up to 700 psig and produced drive gases at manually controlled steam header temperatures up to 530°F.

Three more tests (Run 23, 24, and 25) were conducted on 9, 14 and 16 February 2005, with the goal of achieving higher power levels without an automatic trip caused by a low NG inlet pressure limit. During these tests, power was automatically ramped to achieve power levels of 79, 70, and 85%, respectively (based on fuel flow rates indicated by instrumentation on the GG). Only the last of these tests was automatically terminated and that was caused by a low feed water supply. In these tests the GG operated at automatically controlled pressures up to 780 psig and produced drive gases at manually controlled steam header temperatures up to 600°F.

These test results demonstrated that the DCS could successfully control the GG in automatic pressure and cascade power ramping modes, while under manual temperature control. This was a step-wise test element, gradually increasing the autonomy of the DCS in controlling the GG.

Following successful completion of low-fire testing and initial high-fire testing, the GG and its control system were commissioned. On 28 February 2005 (Run 31) a major milestone was achieved with the first export of power to the grid.

3.1.1.1.3 Automatic cascade power ramping with automatic pressure and temperature control

Test Plan Item 5.3.1.3: Demonstrate normal low-fire startup with drive gases by-passed to the stack. Ramp power to prescribed power levels at a prescribed rate and hold constant. Automatically control steam header pressure and temperature. Multiple power ramps and hold periods may be conducted during a single demonstration. Demonstrations are deemed successful if the desired cascade power ramps are successfully achieved with steam header pressure and temperature under automatic control. Demonstrations may be interrupted by automatic trips and be deemed successful if the trips are due to an improper limit value or an equipment failure outside the GG system.

Test Results: The first automatic power ramp demonstration in this series (Run 37) was conducted on 8 March 2005. The initial stages of power ramping (from ~20 to 27% power levels) were partially performed by stepwise modulation of one or more of the feed valves. Power level was then ramped in a fully automatic cascade mode upward and downward in the range of 27 to 35% power at a rate of 3% per minute and held at fixed power levels for various periods (3-30 minutes). At the end of the test, power was ramped down from 35% to 20% power and held at 20% for 3 minutes. The GG was then commanded to perform an automatic shutdown. The GG operated at automatically controlled pressures up to 400 psig and produced drive gases at an automatically controlled steam header temperature of 450°F.

A second test series (Run 40) was performed on 9 March 2005. It was generally similar to the previous test but involved power ramps to 30, 45, and 55% with intermediate hold periods (10-30 minutes) at constant power. At the end of the test, power was ramped downward from 55% to 20% power at a ramp rate of 3% per minute and held at 20% power for ~2 hours. The GG was then commanded to perform a shutdown because of a low feed water supply. The GG operated at automatically controlled pressures up to 525 psig and produced drive gases at an automatically controlled steam header temperature of 500°F.

These test results successfully demonstrated virtually full-up DCS control of the GG, with all functions automatically controlled except excess O_2 (not part of the test). The test successfully demonstrated automatic power ramping and automatic temperature and pressure control (O_2 held constant).

3.1.1.1.4 Automatic cascade power ramping with automatic pressure and temperature controls and manual control of excess oxygen

Test Plan Item 5.3.1.4: Demonstrate normal low-fire startup with drive gases by-passed to the stack. Ramp power automatically to prescribed power levels at a prescribed rate and hold level. Automatically control steam header pressure and temperature. Manually control excess oxygen in the drive gas based on measured concentration of O_2 in the exhaust products. Manual oxygen control is exercised by modulating the main fuel valve or the fuel trim valve, as appropriate. Multiple power ramps, hold periods, pressures, temperatures, and O_2 concentrations may be assessed during a single demonstration. Demonstrations are deemed successful when the prescribed automatic cascade power ramps are successfully achieved while steam header pressure and temperature are under automatic control and the excess O_2 concentration is manually controlled. Demonstrations may be interrupted by automatic trips and are deemed successful if the trips are due to an improper limit value or an equipment failure outside the GG system.

Test Results: The drive gas sampling system and the oxygen and carbon monoxide (CO) analyzers were successfully brought on stream in early May 2005. This set the stage for testing the ability of the control system to maintain prescribed excess oxygen concentrations in the drive gas. On 18 May 2005, the oxygen control functions were successfully tested in a software simulation mode.

On 31 May 2005 (Run 124), the first full test of the excess oxygen control system (manual mode) was performed. A normal low-fire startup was performed with drive gases by-passed to the stack. Header pressure and temperatures were maintained under automatic control (400 psig, 500°F) and drive gas oxygen was manually controlled, initially ~ 4.5% in excess of stoichiometric. Power was then rapidly ramped to 25% of full power and held constant for 18 minutes. During this interval, drive gas was redirected from the stack to the STG and the STG synchronized to the grid. Header pressure and temperatures were held at 400 psig and 500°F under automatic control.

Manual control of excess oxygen was demonstrated by modulating the main oxygen valve. This was contrary to the original plan—controlling excess oxygen via the main fuel valve or fuel trim valve. This test plan change was made because the fuel trim valve failed to seat properly and the main fuel valve provided less sensitive control than the main oxygen valve. After demonstrating successful manual control of excess oxygen, further testing was performed in the automatic excess oxygen control mode. Oxygen in the (dry) drive gas was automatically controlled during the balance of Run 124 at nominal concentrations of 5, 10, and 15% by volume (equivalent to ~2.5, ~5, and ~7.5% O_2 in excess of stoichiometric). Power levels in automatic excess oxygen control ranged from 30 to 70% of full power, and header pressure and temperatures were maintained under automatic control at 600 psig and 650°F.

This test added manual excess O_2 adjustment to the previous test baseline. These test results demonstrated successful automatic power ramping, pressure, and temperature control while variable amounts of excess O_2 were introduced.

3.1.1.1.5 Automatic cascade power ramping with automatic pressure, temperature, and excess oxygen controls

Test Plan Item 5.3.1.5: Demonstrate cascade power ramping as in 5.4.1.4 except automatically control excess O_2 by modulation of the main fuel valve and/or the fuel trim valve, as appropriate. Define relationship between excess O_2 and CO concentrations in the (dry) exhaust gases from the system. Correlate results with previous bench-scale tests that indicated CO decreases with increasing O_2 concentration. Define an optimal excess O_2 set-point. Demonstrations are deemed successful when the prescribed automatic cascade power ramps are successfully achieved while pressure, temperature, and the excess O_2 concentration are automatically controlled. Demonstrations may be interrupted by automatic trips and are deemed successful if the trips are due to an improper limit value or an equipment failure outside the GG system.

Test Results: Further demonstration of automatic control of excess oxygen at various power levels was accomplished with simultaneous automatic header pressure and temperature control during tests on 1, 2, 3 and 6 June 2005 (Runs 126, 127, 129, and 131, respectively). Automatic control of excess oxygen was exercised by modulating the main oxygen valve rather than the main fuel valve or fuel trim valve, contrary to the original plan, for the reasons described in the preceding section.

During Run 126 (1 June 2005), excess oxygen was automatically controlled at power levels of 30, 40, and 50% of full power while drive gas header pressure and temperature were automatically controlled at 600 psig and 600°F. The oxygen in the dry drive gas was automatically controlled at concentrations in the range of 5 to 10.2% volume (equivalent to 2.5 to 5.1% in excess of stoichiometric). The oxygen set-point concentrations (dry basis) were found to be controllable within a standard deviation of ≤ 1.1%.

During Run 127 (2 June 2005), excess oxygen was automatically controlled at power levels of 40, 45, 55, 70 and 74% of full power while drive gas header temperature and pressure were automatically controlled at 600°F and 600 or 650 psig. The oxygen in the dry drive gas (primarily CO_2) was automatically controlled at concentrations in the range of 8.2 to 15.7% volume (equivalent to 4.1 to 7.8% in excess of stoichiometric). These oxygen set-points were found to be controllable within a standard deviation of ≤ 1.2%.

During Run 129 (3 June 2005), excess oxygen was automatically controlled at a power level of 30% of full power while drive gas header temperature and pressure were automatically controlled at 600°F and 594 psig. The oxygen in the dry drive gas was automatically controlled at various set-points ranging from 6 to 12% volume (equivalent to 3 to 6% in excess of stoichiometric). The concentration of CO was also monitored in this test to define correlations between oxygen and CO concentrations in the drive gas (dry basis) at water injection rates to the generator main injector corresponding to water to oxygen mass ratios (W_i/O) of 1.221 and 1.358. The resulting correlation is shown in the Figure 3.

This correlation shows that the concentration of CO decreases exponentially as the oxygen concentration increases and that a decreasing ratio of water to oxygen injected into the combustion chamber also decreases CO concentrations.

During Run 131 (6 June 2005), excess oxygen was automatically controlled at gas generator power levels in the range of 30 to 48% of full power while drive gas header temperature and pressure were automatically controlled at ~600°F and pressures of 550, ~600 or 650 psig. The oxygen in the dry drive gas was automatically controlled at a set-point of ~10% volume (equivalent to ~5% in excess of stoichiometric) for extended periods while the ratio of water to oxygen injected into the combustion chamber (W_i/O_2) was varied and the concentration of CO was monitored. The data acquired under these test conditions are displayed in Figure 4.

These data show that the CO concentration decreases approximately linearly as the ratio of water to oxygen injected into the combustion chamber decreases. Because the effective temperature in the combustion chamber increases as the ratio of injection water to O_2 (and fuel) decreases, it follows that CO emissions decrease in response to increasing combustion temperature.

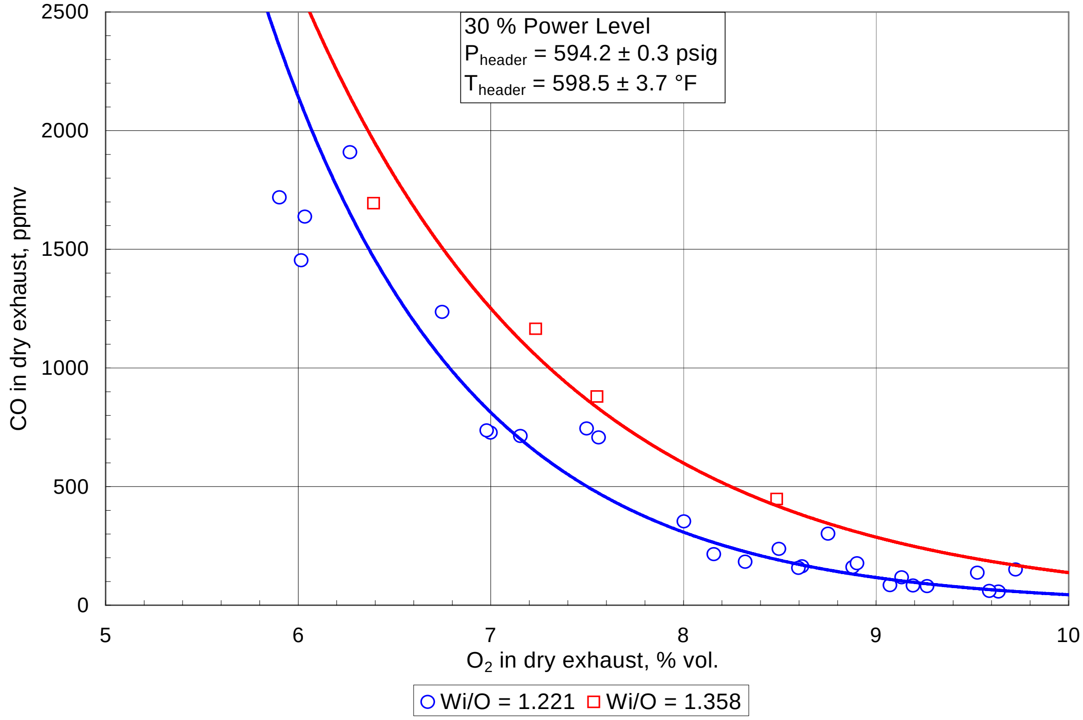


Figure 3. Effect of Excess Oxygen on the Concentration of CO in Dry Exhaust Gases

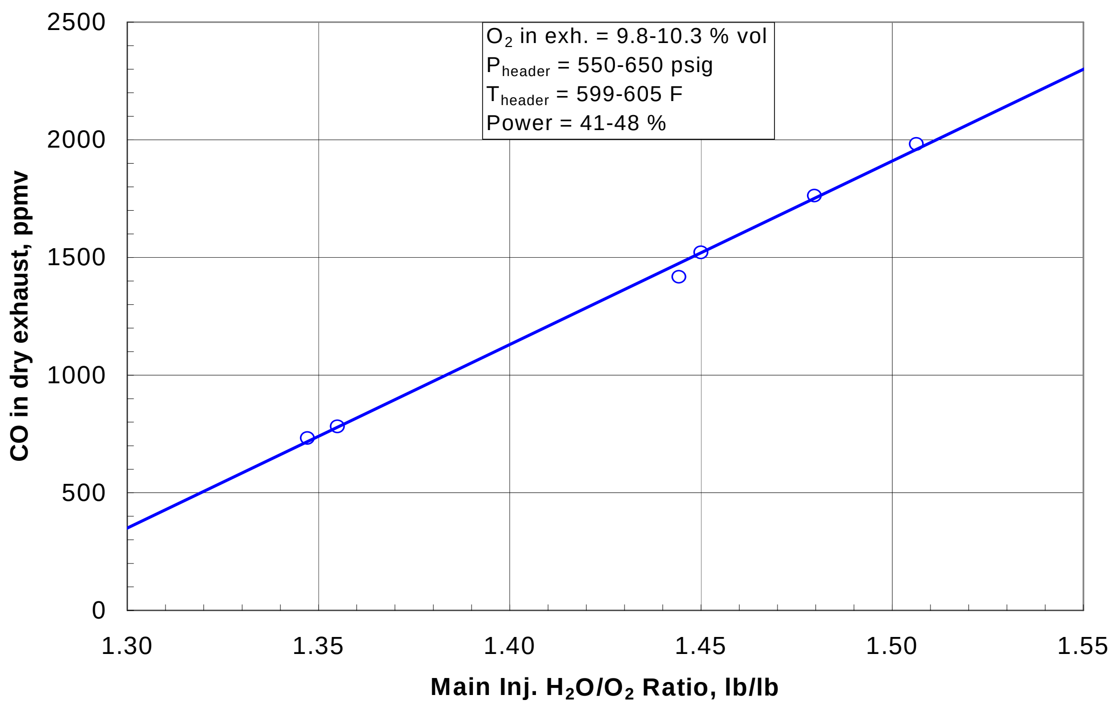


Figure 4. Effect of Water/Oxygen Ratio on CO Concentration in Dry Exhaust Gases

3.1.1.2 Series 2: High-fire tests with drive gases directed to the steam turbine

Test Series 2: In this test series, the drive gases were directed to the steam turbine/generator (STG) for grid synchronization and power generation to demonstrate:

1. Gradual switching of GG drive gases from the stack to the stream turbine with grid synchronization and power production.
2. Drive gas generation in a GG power-command mode of operation for power production.
3. Drive gas generation and power production in an (electrical) power-following mode of operation, and
4. Drive gas generation and emergency GG shutdown in a turbine trip situation. The series encompassed four successful tests. These tests are further described below.

3.1.1.2.1 Switch GG drive gases to the steam turbine and production of electricity

Test Plan Item 5.3.2.1: Demonstrate normal low-fire startup with drive gases by-passed to the stack. Ramp power manually or automatically to achieve prescribed turbine time/temperature/speed profiles. Automatically control steam header pressure and temperature at desired values. Bring the turbine to synchronous speed and synchronize with the grid (or a portable generator, if connection to the grid is not permitted). The demonstration is deemed successful when the turbine is synchronized with a 60 Hz power system and power is delivered to the system while the GG is operating under automatic control.

Test Results: Drive gases from the GG were first diverted to the steam turbine on 21 December 2004 in the course of a 2.78-hour low-fire test of the GG. That test encompassed use of virtually all KPP subsystems, including the NG compressor, O_2 supply, and feed water pump. Approximately 1.6 hours into the test, the steam valve to the turbine was opened and GG drive gases were gradually diverted from the by-pass circuit to the turbine as the rotational speed of the turbo-generator was increased in accordance with its established startup procedure. Approximately 2.4 hours into the test with the turbine rotating at 2,200 RPM, GG power level was gradually increased by manually opening the modulating O_2 and NG valves. As power level increased to ~25% with a drive gas pressure of 365 psig and temperature of 550°F, the STG reached and held synchronization speed. The turbo-generator was ready to produce power though it failed to achieve synchronous lock with the portable generator being used for plant power.

On 28 February 2005 the gas generator was ramped to ~55% power level under automatic control and its drive gases were redirected to the turbine. The turbine was brought to synchronous speed, synchronized with the grid, and where it delivered minimal power to the grid on four separate synchronizations.

These test results demonstrated that the GG could proceed successfully from ignition through low fire (with all drive gases exiting via the by-pass stack) and then transition to providing drive gas through the steam turbine as the by-pass valves closed. It also demonstrated the ability of the GG to compensate for pressure and temperature changes as the turbine was ramped up to synchronous speed, through synchronization with the grid, and the production of electrical power.

3.1.1.2.2 Drive gas generation in GG power-command mode of operation and power production

Test Plan Item 5.3.2.2: Demonstrate normal low-fire startup with drive gases by-passed to the stack. Ramp power manually or automatically to achieve prescribed turbine time/temperature/speed profiles. Automatically control steam header pressure and temperature at desired values. Bring turbine to synchronous speed and synchronize with the grid (or a portable generator if connection to the grid is not permitted). The demonstration is deemed successful when the turbine is synchronized with a 60 Hz power system and significant net power is delivered to the system while the GG is operating under automatic control in a power-command mode.

Test Results: On 3 March 2005, GG power was ramped upward under automatic control and its drive gases were partially, and subsequently fully, diverted to the turbine. The turbine was brought to synchronous speed and synchronized with a portable generator that was supplying power to the plant. The power level of the GG was gradually increased until the turbo-generator supplied the plant's entire parasitic load. KPP was operated in a "power island" (i.e., stand alone mode) for several hours before the system tripped on a false high O_2 supply pressure indication.

On 15 March 2005 the GG was ramped up under automatic control and its drive gases gradually diverted to the turbine. The turbine was brought to synchronous speed and synchronized with the grid. The power level of the GG was then increased with all the drive gases directed to the turbine until the STG was supplying the plant's entire parasitic load and exporting ~1 MW_e to the grid. A turbine trip eventually terminated this test which resulted in an automatic, safe shutdown of the GG.

These test results were similar to the previous test. The test demonstrated the reliability of the GG in startup operations, successful ramping of the steam turbine to synchronous speed under automatic DCS control, synchronization with the grid, and exporting of significant power (1 MW_e).

3.1.1.2.3 Drive gas generation & power production in an electrical power-following mode of operation

Test Plan Item 5.3.2.3: Demonstrate normal low-fire startup with drive gases by-passed to the stack. Ramp power manually or automatically to achieve prescribed turbine time/ temperature/ speed profiles. Automatically control steam header pressure and temperature at desired values. GG power level is manually or automatically ramped upward as necessary to achieve prescribed turbine time/temperature/speed profiles. Bring the STG to synchronous speed and synchronize with the grid. STG electrical load is increased by the STG control system, and the GG maintains pressure control by increasing mass flow (oxygen, fuel, and water) for power load increases and decreases mass flow for power load reductions. The demonstration is deemed successful when the turbine is synchronized with and power is delivered to the grid while the GG is operating under automatic control in an electrical load-following mode of plant operation.

Test Results: On 6 June 2005 (Run 131), the gas generator was started under normal low-fire conditions with the drive gases by-passed to the stack. Power was ramped upward from low-fire conditions (~20% power level) in an automatic cascade mode to approximately 25% power and held for ~15 minutes then ramped to 30% power and held for ~1 hour. During the latter power-hold period, steam was diverted to the turbine and the STG was synchronized to the grid. Power was then ramped automatically in cascade mode to 40% power (~1.1 MW_e to the grid) with the steam header temperature under automatic control at 600°F and oxygen under automatic control at 5% in excess of stoichiometric. The control system was then switched to the power-following mode of operation wherein the mass flow rate of drive gases automatically increases and decreases in response to power demand.

For demonstration purposes, changes in power demand were commanded by changing the steam header set-point pressure. This caused the control system to automatically modulate the oxygen, natural gas, and water injection valves and thereby change the mass flow rate of the drive gas and maintain the steam header set-point pressure. Figure 5 shows that the gas generator automatically responded to increasing and decreasing demands for drive gas flow and power as steam header pressure deviated from given set-points. Steam header temperature and excess oxygen (i.e., over stoichiometric requirement) was simultaneously under automatic control at 600 ± 12°F and 5.0 ± 1.5% excess O_2. Response times to step changes in power demand were observed to be ~80 to 90 seconds. The electrical power output in the power-following mode of operation and the corresponding thermal output requirement on the gas generator are shown in Figure 6 as functions of turbine drive gas flow rate.

These test results demonstrated that the DCS and GG would automatically maintain required drive gas flow temperature and pressure while in an electrical load-following mode of operation. In this mode, the GG responds to the turbo-generator, increasing power to maintain frequency synchronization when electrical demand increases, and reducing power as electrical load decreases. This mode of operation is critical to support central dispatching of CES power plants.

3.1.1.2.4 Emergency GG shutdown caused by a turbine trip or power outage

Test Plan Item 5.3.2.4: Demonstrate automatic and safe shut down of the GG whenever (1) a turbine trip causes a pressure excursion of the GG drive gases in excess of limit value (kill pressure) or (2) a power plant power outage occurs. Turbine trips were anticipated to occur in the course of performing the demonstrations described in the preceding sections. Power outages may be simulated, if necessary.

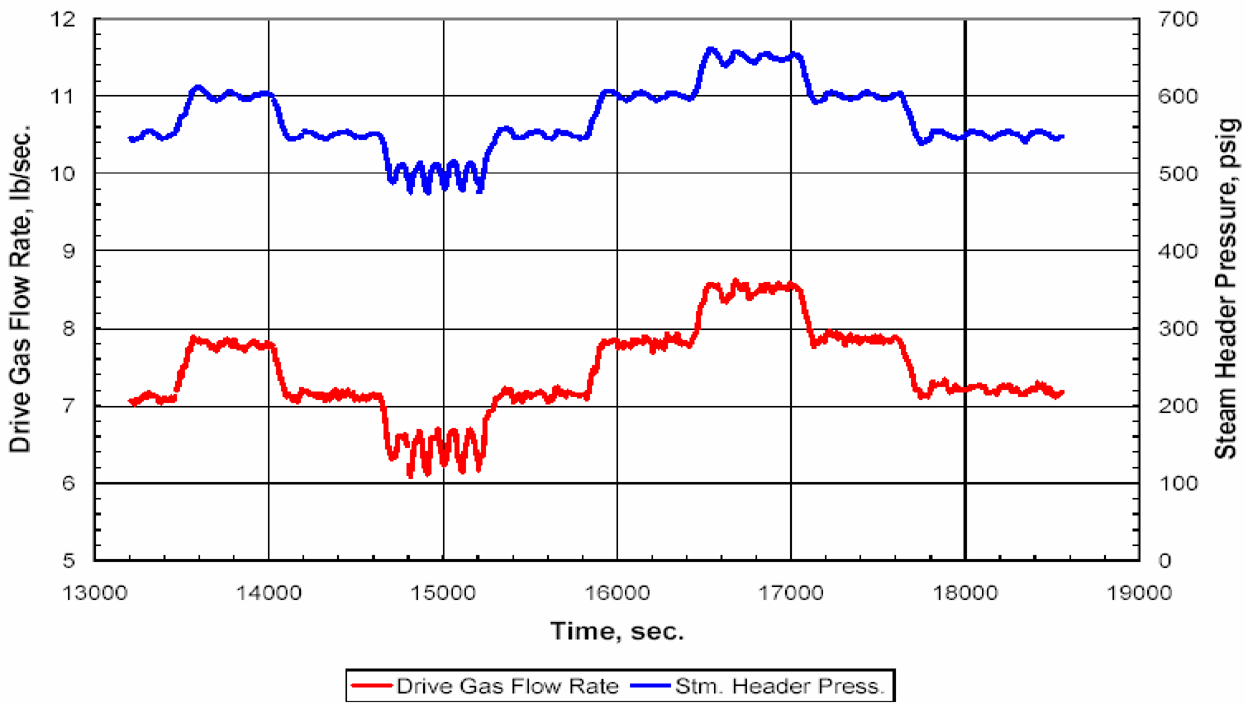


Figure 5. Drive Gas Mass Flow Rate and Steam Header Pressure

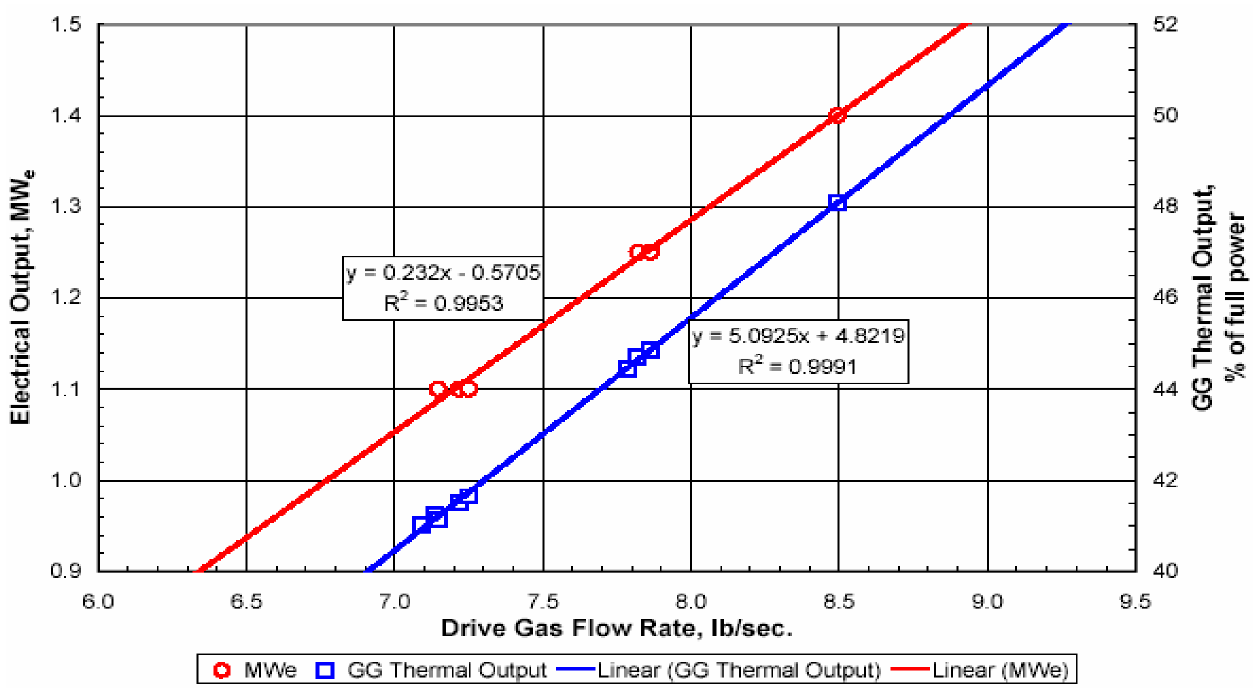


Figure 6. Electric Power and GG Thermal Output as Functions of Drive Gas Flow Rate

Test Results: During the course of synchronizing the KPP electrical generator to the grid, one STG trip and two total plant power outages occurred. In addition, three drive gas (steam) high-pressure trips occurred. Those trips are equivalent to the result of a STG trip while operating at high power output. In each case, the GG control system executed an automatic and safe emergency GG shutdown. Post shutdown inspections showed no GG damage and normal GG operating configuration.

3.2 Refinement and Adjustment of the Control System

The controls for the GG system were refined and adjusted in the course of the commissioning and durability demonstration efforts in a number of significant ways. These refinements and adjustments were made in four broad categories: (1) data acquisition, (2) sequencing and kill parameters, (3) control loops, and (4) human machine interface (HMI).

3.2.1 Data acquisition

The data acquisition capabilities of the original control system were relatively limited. The system read data from various sources (data channels) and used those data for controller actions but did not store a significant amount of that information in a readily downloadable form for subsequent analyses. The data acquisition capabilities were therefore upgraded to acquire fast data and slower trending data.

The new fast data acquisition system captured digital signals from all channels at nominal 25-msec intervals (40 Hz) during the critical initial 50 seconds of the startup sequence and for the 50 seconds following a signaled shutdown. This capability provided separate automatically archived startup and shutdown files for every run. These data were available for subsequent detailed analysis which greatly aided in both trouble shooting, particularly during commissioning, and later to check the consistency/repeatability of critical valve operating responses during startup and shutdown operations.

The trending data acquisition system was added to capture digital signals from all channels at 1-second intervals (or other programmable interval) and store those data on a separate computer. A separate data storage device was necessary because of the large memory requirements. These large files were then downloaded to CDs (compact disks) or DVDs (digital video disks) as desired to provide long-term trending data for subsequent system performance evaluations.

3.2.2 Sequencing and kill parameters

The proper sequencing of startup and shutdown valve operations is a particularly critical task for the GG control system. Equally important are the “kill parameters” and the associated “kill” values that are used to signal an automatic shutdown. The basic structure of these control features and place-holder values for sequencing times and “kill” values were part of the original control system, but real values were defined as part of the commissioning effort.

Previous testing experience on the stand-alone GG provided a good starting point for acceptable and/or desired start and shutdown sequence operations, but new control components (valves and instrumentation) at the Kimberlina facility required refinement of valve timings appropriate to the new installation. Generally, these refinements were facilitated by conducting specific valve timing tests under cold-flow conditions (i.e., operating flow circuits on water or inert gases). Subsequently, further refinements were made in the course of conducting igniter tests, low-fire hot tests, and high-fire tests. Specific details of the operating sequences and timings are considered to be intellectual property of CES.

Previous testing experience, similarly, provided a good starting point for acceptable and/or desired "kill parameters" and the associated "kill" values. Refinements to those items evolved in the course of commissioning and later durability testing. Specific details of the structuring of the "kill" logic, "kill parameters", and "kill" values during the various stages of startup and normal operation are considered to be intellectual property of Clean Energy Systems, Inc.

3.2.3 Control loops

The programmable logic controller (PLC) in the original control system contained basic logic for the various automatic control loops envisioned for the Kimberlina facility. Those control loops included drive gas pressure and temperature to the steam turbine (or by-pass circuit), power ramping and holding, excess oxygen, and power-following.

As commissioning progressed, two different drive gas pressure control loops were found to be necessary. One control loop maintained pressure by modulating by-pass valves when all or a portion of the drive gas was diverted directly to the stack. Another control loop maintained drive gas pressure to the steam turbine by modulating fuel, oxygen, and several water injection valves when the by-pass valves were closed. Drive gas temperature control was maintained by modulation of water flow to the last two water injection circuits. A power ramping control loop was also developed that allowed power to be increased or decreased incrementally by manual adjustment of the power set point or by automatic ramping to a new set point at a programmable rate. A modified version of that loop also permitted a power-following mode of operation. In both cases, the control loop modulated fuel, oxygen, and several water injection valves in unison. The excess oxygen control loop modulated the oxygen feed valve in response to feedback from an oxygen analyzer sensing a conditioned sample of drive gas at the "steam" header from the GG or, optionally, from a gas sample from the CO_2 exhaust exiting the liquid-ring vacuum pump.

The majority of the development, refinement, and adjustment of the control loops described above was performed in the course of testing directed toward system turnover and commissioning efforts. That testing is described in detail in Section 3.1.

3.2.4 Human machine interface (HMI)

During the latter part of the GG system commissioning effort and continuing through the durability testing, numerous improvements were made in the HMI to make the operation of the GG system more operator-friendly. The improvements were geared to both make the system very simple to operate and to make all import operating information available in a clear and concise manner. Provisions were also made to allow the operator to call up monitoring screens with more detailed GG system operating information or information on the status of the fuel, oxygen, and water supply systems to the GG system.

The HMI at the end of this program featured a computer workstation with two large flat-screen displays. One screen normally displays a diagram of the GG system with operating conditions at all key points overlaid. Changes to certain operating set points are made by simply selecting the desired variables and entering new set points. The main screen also indicates when certain operating parameters are approaching automatic "kill values" so the operator has some opportunity to take potentially necessary remedial action. Additionally, the screen displays the operating phase of the GG (i.e., pre-purge, purge, post-purge, ignition, low-fire, or high-fire). In the case of an automatic shutdown, the particular phase, "kill parameter", and "kill value" are indicated to make the cause of the shutdown readily evident.

The other screen allows the operator to separately view a GG sub-screen containing more detailed operating information such as control loop parameters or to display diagrams of the fuel, oxygen, and water supply systems.

3.3 Demonstration of Durability and Reliability

3.3.1 Durability

The long-term durability tests identified as Items 7.1.1–7.2 in the Test Plan (Table 1) generally occurred during the period from 28 February 2005, KPP's first export of electrical power to the grid, through 29 March 2006 and run numbers 31 through 413. Over the course of all the testing, the GG was started ~300 times (i.e., achieved at least 20% of full power) and accumulated a total of 1,333 hours of operating time. All 413 of the "runs" performed under this program are listed in Appendix A. This listing identifies the test by "Run No." and "Start Date" and defines the GG output in terms of percentage of full design power (~16 MW_t) and electrical power sent to the grid (MW_e). The listing also defines the "Run Time", provides comments on the shutdown circumstances, and identifies the subsystem causing each shutdown.

In 16 of the so-called "runs", the actual GG start sequence was not initiated (run times of zero). In another 103 runs, the tests were automatically terminated by the GG control system prior to achieving the low-fire power level (20 % of full power[†]). Eighty-three of the premature shutdowns were automatically tripped by the control system in less than 30 seconds of initiating the start sequence. Another 16 runs were terminated in less than 60 seconds and the other four runs were terminated in less than 2 minutes.

Automatic trips were commanded by the control system when any monitored GG operating parameter (e.g., temperature, pressure, flow rate, etc.) did not meet prescribed limit values (high and/or low "kill" limits) during particular time intervals and various phases of the operating sequence. In many cases, the limit values programmed into the control system were

[†] Power outputs as given throughout this report are based on the GG fuel flow meter and may be lower than actual values by about 15 % if the gas supply company's gas meter is assumed to be correct.

intentionally set at very conservative values to provide added safety margins to protect personnel and equipment. This conservatism and "safe rather than sorry" operating philosophy resulted in a number of unnecessary shutdowns but contributed to a perfect safety record and demonstration of long-term durability.

The only significant damage to the GG occurred very early in the commissioning phase of the testing effort (following Run 6 on 21 December 2005) and was the result of human error in altering the run program to conduct a special test. The program change allowed the fuel and oxygen valves to reopen after an automatic trip/shutdown sequence but did not allow the water injection valves to open. This resulted in an unplanned GG restart without water injection cooling that caused damage to the injector face. No significant damage was sustained by any other GG component. The damaged injector was replaced with a spare and testing resumed without any further incidents. The incident was unfortunate and that particular GG failure mode (i.e., combustion without injection of cooling water) is among the most severe envisioned in a FMEA (failure modes and effects analysis) performed prior to starting the test program. Nonetheless, the fact that hardware damage was minimal and no personnel were endangered attests to the safety and durability of the GG system.

The duration of the individual test runs ranged from less than 1 minute to 105 hours. Power levels ranged from 20 to 88% of full power during 1,333 hours of GG operation. Power was exported to the electrical grid at power levels from 0.5 to 2.7 MW_e during 141 runs encompassing 1,243 hours of GG operation. The GG operated continuously for periods greater than 8 hours in 43 of these runs, covering a total of 817 hours of operation and for periods greater than 24 hours in 11 runs totaling 445 operating hours.

Representatives of two major insurers of power plant equipment (AON and Liberty International) toured the Kimberlina plant and reviewed the operating records of the GG system (number of starts, operating hours, shutdown circumstances, maintenance experience, and inspection results). That tour and inspection resulted in their declaration that the GG system is insurable. This is an independent verification that the GG system poses no unusual risk in a power plant

3.3.2 Reliability

Successful GG runs (i.e., achieving at least 20% of full power) at power levels from 20 to 88% of full power were achieved in 294 tests during 1,333 operating hours. The causes, frequencies, and the run times associated with the various types of shutdowns are summarized in Table 2.

Table 2. Causes, Frequencies, and Effects of Test Terminations

System Causing Run Termination	Run Terminations		Interrupted Run Time	
	No.	%	Hours	%
None (normal shutdown)	107	36.4	610.8	45.8
GG Subsystem	71	24.1	172.2	12.9
O_2 Supply	66	22.4	366.8	27.5
Electrical Syst.	13	4.4	40.9	3.1
H_2O Supply	13	4.4	10.0	0.8
NG Supply	12	4.1	111.7	8.4
Steam	4	1.4	1.0	0.1
Human	4	1.4	3.0	0.2
Turbine/Gen.	3	1.0	16.1	1.2
Undefined	1	0.3	0.3	0.0
Totals	294	100	1332.9	100.0

In 107 (36%) of these tests, the shutdowns were fully voluntary because of successful completion of test goals and encompassed ~611 hours of GG operation. Seventy-one (24%) of the tests were terminated for causes attributable to the GG system. Fifty-four of those tests covering 54 operating hours were automatically terminated by the control system because an apparent GG operating parameter did not meet a prescribed limit value, another 13 runs covering 111 operating hours were terminated to repair observed water leaks, and 4 runs were terminated for miscellaneous reasons. Most of the automatic run terminations by the control system were the result of having overly conservative "kill parameters" in the control software or because of sensor failures.

The oxygen supply system was the other major cause for shutdowns of GG operations, causing the termination of 66 (22%) of the test runs covering 367 operating hours. The electrical systems and feed water supply system caused the termination of 13 test runs each (4.4% each) covering 41 and 10 operating hours, respectively. The natural gas supply system caused the termination of 12 test runs (4.1%) covering 112 operating hours. The steam system (lines and valves) and human error caused the termination of four runs each (1.4% each) covering 1 and 3 operating hours, respectively. The turbine/generator system caused the termination of three test runs (1%) covering 16 hours of operation.

Ninety-four tests of greater than 4-hour duration each and covering a total of 1,123 hours of GG operation (84% of total operating experience) were performed under this program. Of those 94 tests, only 10 were terminated because of a GG system and five of those were terminated by the operator to repair simple water leaks. GG-initiated run terminations dropped dramatically following GG system commissioning on 6 June 2005 (Run 131). After that date, only two tests were terminated because of GG system faults during 76 tests of greater than 4-hour duration each and 1,014 hours of operation.

3.4 Drive Gas Composition

3.4.1 Carbon monoxide (CO) emissions

The CO emissions of the GG system were first measured during commissioning Runs 129 and 131 (3 June and 6 June 2005). Those tests are described in Section 3.1.1.1.5 and the test results are displayed in Figures 3 and 4. The data from Run 129 showed that CO emissions increase with decreasing O_2 concentration in the drive gases as expected, and analytically correlate well as a power function of the O_2 concentration, i.e., $CO \cong a(O_2)^b$. The data from Run 131 showed that CO emissions increase approximately linearly as the ratio of water to oxygen injected into the combustion chamber increases. This response is a reflection of the fact that increasing water injection flows translate into decreased combustion temperatures, which are well known from experience with water or steam injection into gas turbines to increase CO emissions.

In the course of performing durability and off-design tests, the effect on CO emissions of changing the type of the first diluent injector in the GG was evaluated at various levels of excess oxygen and main chamber injection water-to-oxygen ratios. The water injectors used in each cooldown chamber for the major portion of the tests were of an edge-spray type while the latter tests employed a finger-type water injector at the forward end of the first cooldown chamber. These two diluent injector configurations are shown in Figure 7.

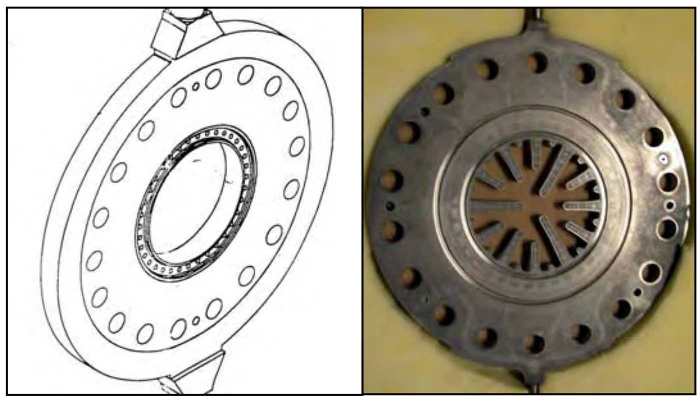


Figure 7. Edge-Spray and Fingered Diluent Injectors

The effect on CO emissions of changing the type of injector for the first cooldown chamber is shown in Figure 8, which plots the CO emissions side-by-side for the different hardware configurations under the same set of operating conditions. These data indicate that the fingered injector significantly decreases CO emissions when the GG is operated at excess oxygen concentration less than ~6 % (the generally preferred operating region) but may not offer an advantage at higher O_2 concentrations in the dry exhaust. The CO emissions when using the fingered diluent injector are also displayed in the left graphs in Figures 9 and 10 in units that are more readily comparable to those used to define CO emissions from gas turbine power generation systems. In Figure 9, the CO emissions are expressed in terms of pounds of CO per million Btu and show that the measured values ranged from ~0.02 to 0.31 over a wide range of GG system operating conditions. The emissions of CO tend to increase when the GG system is operated at higher power levels.

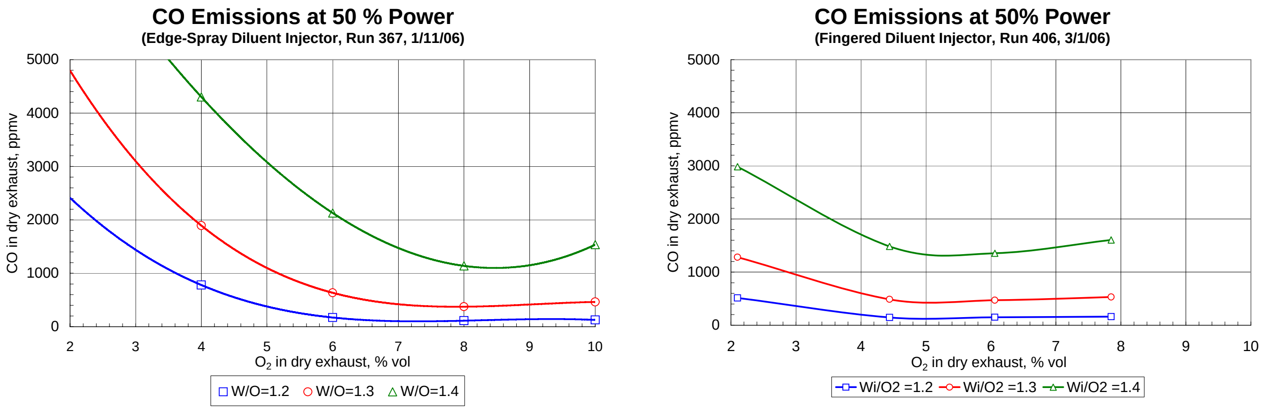


Figure 8. CO Emissions at 50% Power with Different Types of First Diluent Injectors

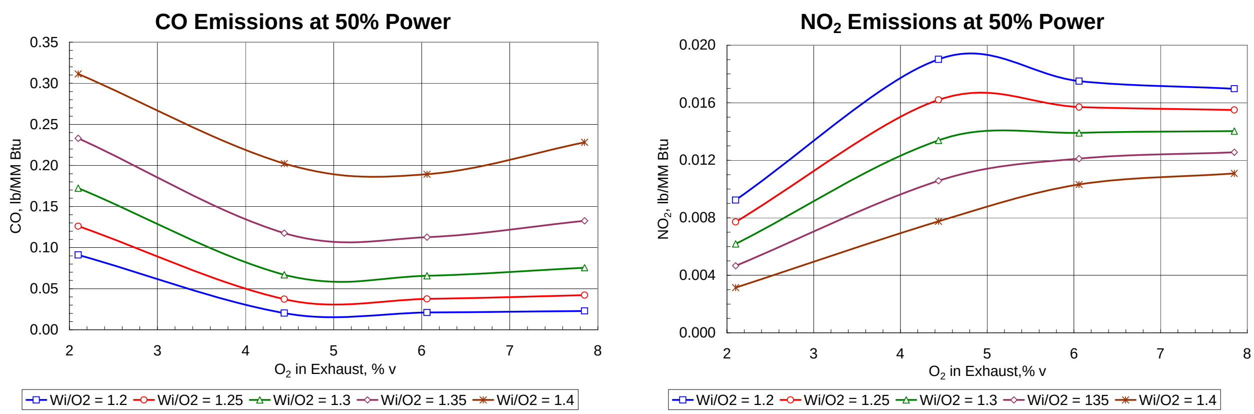


Figure 9. CO and NO_2 Emissions at 50% Power under Various Operating Conditions in lb/MM Btu

In the left plot of Figure 10, the CO emissions are expressed in terms of parts per million by volume (ppmv), corrected to 15% excess O_2 . This is the measure normally used for emissions from conventional engines and gas turbines. This figure shows the CO emissions from the GG system ranged from ~5 to 80 ppmv on a gas turbine comparable basis.

3.4.2 Nitrogen oxide (NO_x) emissions

In concept, the CES system would produce no NOx emissions because no nitrogen is present in the combustion chamber when NG is combusted in pure O_2 in the presence of DI water. CES investigated the possibility of small quantities of N_2 being introduced into the combustion chamber by the presence of N_2 in pipeline NG and liquid O_2. In practice, CES found that only NG contributed measurable N_2 (0.53-0.66% by volume). Cryogenically derived liquid O_2 had only 0.005% N_2, which is statistically insignificant.

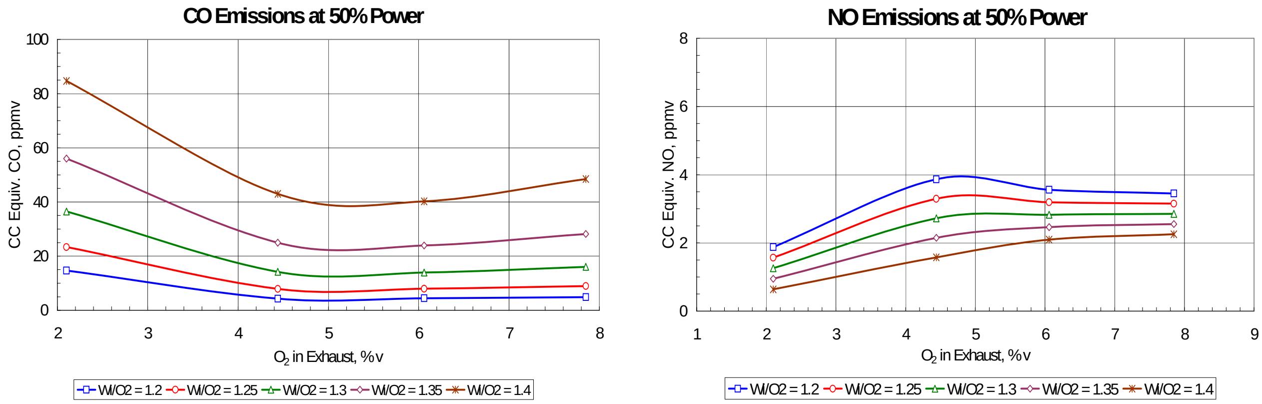


Figure 10. CO and NO Emissions in ppmv, Corrected to 15% O_2, at 50% Power Under Various Operating Conditions, for Comparison with Gas Turbines

The emission of nitric oxide (NO) from the GG system was measured under various operating conditions using the fingered diluent injector at the entrance to the first cooldown chamber and edge-spray diluent injectors for the second through fourth cooldown chambers. The NO emissions when operating the GG at 50% of rated power are displayed in the right plots in Figures 9 and 10. In Figure 9, the NO emissions are expressed in terms of equivalent pounds of NO_2 per million Btu and show that the measured values ranged from ~0.003 to 0.019.

In the right plot of Figure 10, NO emissions are expressed in terms of ppmv at 15% O_2. This figure shows the NO_x emissions from the GG system ranged from ~0.3 to 4.0 ppmv on a gas turbine comparable basis.

It is noteworthy from Figures 9 and 10 that the emissions of CO and NO_x move in opposite directions under slightly lean operating conditions as the fuel-oxygen ratio varies. The lowest CO emissions occur in the range of 4.5-7.0% excess O_2 by volume, and increase as excess O_2 is reduced (to the left), approaching stoichiometric conditions. The lowest NO emissions are achieved as excess O_2 is reduced below 4% by volume, approaching stoichiometric conditions.

The observed emissions of CO and NO_x for the oxy-fueled GG system reached levels lower than the very best observed in combined cycle power systems operating on natural gas and using SCR for NO_x control. Strategies for further decreasing the emissions of CO and NO_x from this first-generation GG system have been formulated and will be experimentally evaluated in future testing efforts. While such emissions reductions are of primary interest in peaker plants where exhaust gases are vented to atmosphere, they may also be desirable in closed-cycle plants by reducing the cleanup burden on CO_2 recovery systems.

3.4.3 Unburned hydrocarbon emissions

The measurement of the emission of unburned hydrocarbons (volatile organic compounds [VOCs]) was not an objective of this program, but grab samples of dry exhaust gas were occasionally taken and submitted for analysis by an outside laboratory, Aero Environmental, Inc. (Project 077-4608B, Jan. 5, 2006). The gas samples were taken during Run 357 while operating the GG at 70% power level at an injection water to fuel mass ratio of ~1.35 with all edge-spray diluent injectors. The resulting data are summarized in Table 3.

Table 3. Analysis of Dry Exhaust Gases

Component	Units	Sample		Analysis Method
		No. 1	No. 2	
CO_2	% vol dry	95.8	93.6	Orsat Analysis
O_2	% vol dry	2.5	5.7	fuel cell analyzer
N_2	% vol dry	1.2	0.7	by difference
H_2	% vol dry	0.5	0	GC-TCD
CO	ppmv dry	3840	430	gas filter correlation analyzer
NO_x ($NO + NO_2$)	ppmv dry	24	28.5	chemiluminscent analyzer
NO_2	ppmv dry	19	23.5	chemiluminscent analyzer
NO	ppmv dry	5	5	chemiluminscent analyzer
C_1	ppmv dry	31	59.5	GC-FID
C_2	ppmv dry	<1	<1	GC-FID
C_3	ppmv dry	<1	<1	GC-FID
C_4	ppmv dry	<1	<1	GC-FID
C_5	ppmv dry	<1	<1	GC-FID
C_{6+}	ppmv dry	<1	<1	GC-FID

Samples 1 and 2 containing 2.5% and 5.7% O_2 by volume correspond to conditions during which the GG was operating at ~1.25% and 2.85% O_2 in excess of the stoichiometric requirements for complete fuel combustion, respectively. From Table 3 it can be seen that the VOC concentrations in the dry exhaust (primarily CO_2) for the two different stoichiometries were ~31 and 60 ppmv. Those concentrations are equivalent to values of ~0.9 and 1.8 ppmv at 15% O_2, the standard normally used for gas turbine powered systems, such as peaker and combined cycle power plants. A representative sample of allowable VOC emissions for five gas turbines permitted in southern California (in December 2001, January 2004, and February 2004) indicated BACT VOC emissions of 2.0 ppmv at 15% O_2.

It can also be seen that the CO concentrations in these samples were 3,840 and 430 ppmv (equivalent to values of ~110 and 13 ppmv at 15% O_2). These values, corrected to 15% O_2, are roughly twice those shown in the left graph in Figure 10, but the higher CO concentrations reflect the facts that higher power levels (70% versus 50%) and use of the edge-spray diluent injector both tend to increase CO emissions.

As noted in earlier sections, CO concentrations ranged from 5-80 ppmv (corrected to 15% O_2) under most CES test conditions without the use of supplement clean-up. This relatively wide range of CO emissions was a result of CES experimental testing seeking operating boundaries. In normal operations, the CES GG would be operated at significantly lower CO emission levels. Should desired CO emission levels not be readily attained with additional control and fuel-water ratio tuning, CES could utilize simple catalytic converters to reduce CO to 1.0 ppmv (~20:1 reduction). In comparison, with catalytic converters and SCR, the five gas turbines mentioned above that were permitted in southern California in 2001 and 2004 were required to meet CO emissions ranging from 2.0 to 6.0 ppmv.

NO_x concentrations in the two gas samples (Table 3) were 24 and 28.5 ppmv (equivalent to values of ~0.7 and 0.8 ppmv at 15% O_2). These values are somewhat less than those shown in the right graph in Figure 10, but are consistent with fact that the CO values in Table 3 are higher those shown in the left graph in Figure 10 (i.e., CO and NOx emissions tend to move in opposite directions with changing operating conditions). The five gas turbines recently permitted in southern California had average permissible NO_x emissions limits of 2.0 ppmv.

3.5 Temperature Profiles of Drive Gases

In the course of performing durability and off-design tests, the effect of changing the type of the first diluent injector in the GG (described in Section 3.4.1) on the radial temperature profiles in the drive gas was studied. The radial temperature profiles near the exit of the third cooldown chamber are shown in Figure 11.

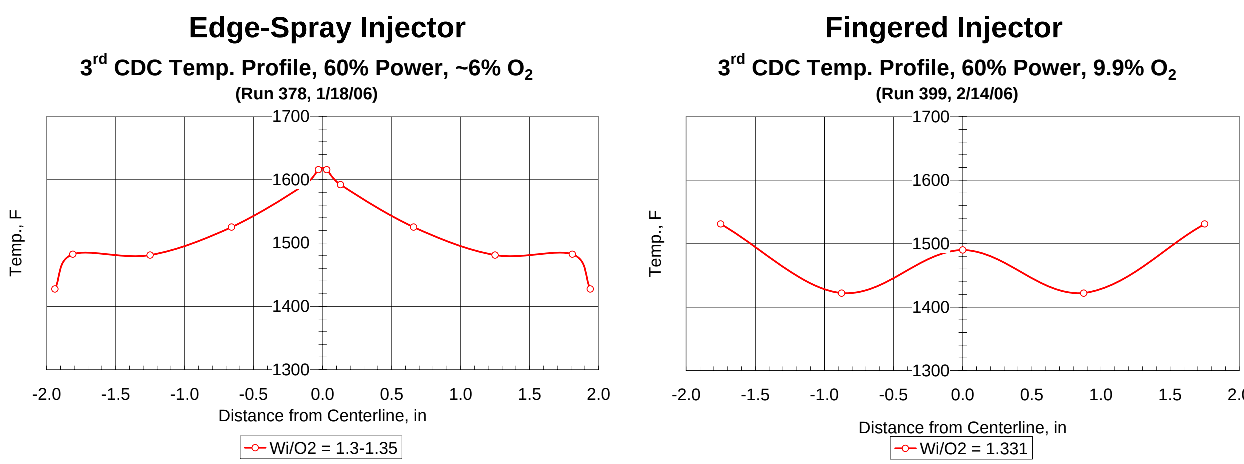


Figure 11. Temperature Profiles in Third Cooldown Chamber (CDC) at 60% Power with Edge-Spray and Fingered Diluent Injectors in the First CDC

Measurements of temperature profiles downstream of the first and second cooldown chambers were precluded because the higher temperatures were expected to damage or destroy the available instrumentation. Unfortunately, the intervening edge-spray-type diluent injectors at the entrance to the second and third cooldown chambers tend to obscure the anticipated temperature smoothing effect of the upstream fingered diluent injector. Even considering the obscuration effect of the intervening edge-spray-type diluent injectors, Figure 11 provides a strong indication that fingered diluent injectors improve radial mixing and smooth the radial temperature profile. The reduction of the "hot core" characteristic when a fingered injector is substituted for an edge-spray injector is highly desirable. As a result, CES is using the fingered injector in on-going GG testing and will use this design for future GG systems.

In subsequent tests with the fingered diluent injectors in place, similar temperature profiles based on added data points were measured over a range of power levels, injection water-to-oxygen mass ratios (W_i/O_2), and excess oxygen concentrations. Typical temperature profiles at 60% power and W_i/O_2 values ranging from ~1.2 to 1.4 at oxygen concentrations of ~8% and 4% in the dry exhaust gases are shown in the two graphs in Figure 12. The profiles are similar in shape in each case, the most notable difference being that the average temperature increases as the W_i/O_2 ratio decreases. As discussed above, the intervening edge-spray-type diluent injectors at the entrance to the second and third cooldown chambers tend to obscure the anticipated temperature smoothing effect of the upstream fingered diluent injector.

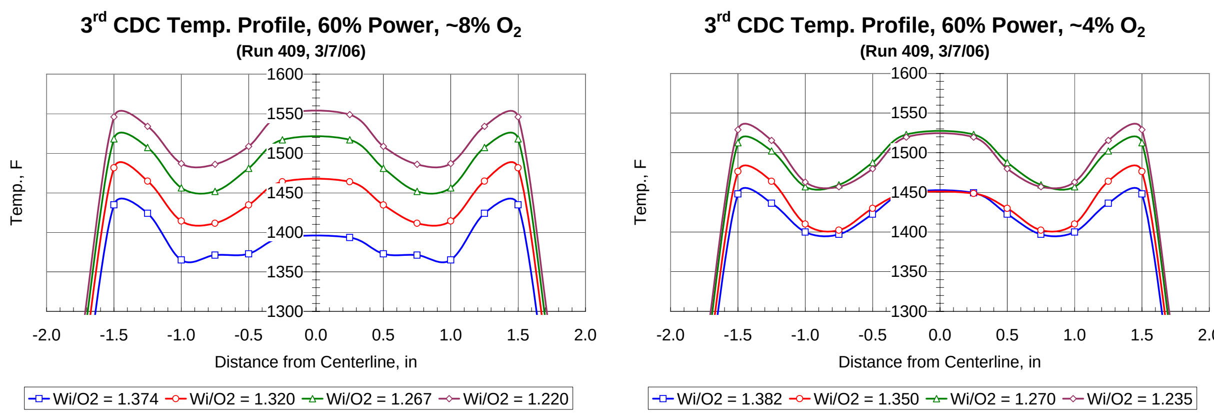


Figure 12. Temperature Profiles in Third Cooldown chamber (CDC) at 60% Power Under Various Operating Conditions with Fingered Diluent Injector in the First CDC

3.6 Condensate Quality

The GG exhaust gas that drives the turbine is a mixture of steam and CO_2. After passing through the turbine, the water is condensed and re-used as diluent water in the GG. CO_2 is dissolved in this condensate, making it slightly acidic through the formation of carbonic acid. To minimize corrosion, CES uses Inconel, stainless steel, or chlorinated polyvinyl chloride (CPVC) for all wetted surfaces. In-line resin beds (polishers) protect the condensate from contamination should the condenser suffer internal cooling water leaks (water used in cooling circuits to condense turbine exhaust steam is not of sufficient quality to be used by the GG).

While operating the power plant under various conditions, the conductivity and pH of the condensate were measured at two locations: as directly recovered from the condenser, and after polishing via ion exchange beds. These data are summarized in Table 4 when the plant was operated at 30% to 60% of full power. The conductivity of the condensate before and after polishing is shown as a function of pH in Figure 13.

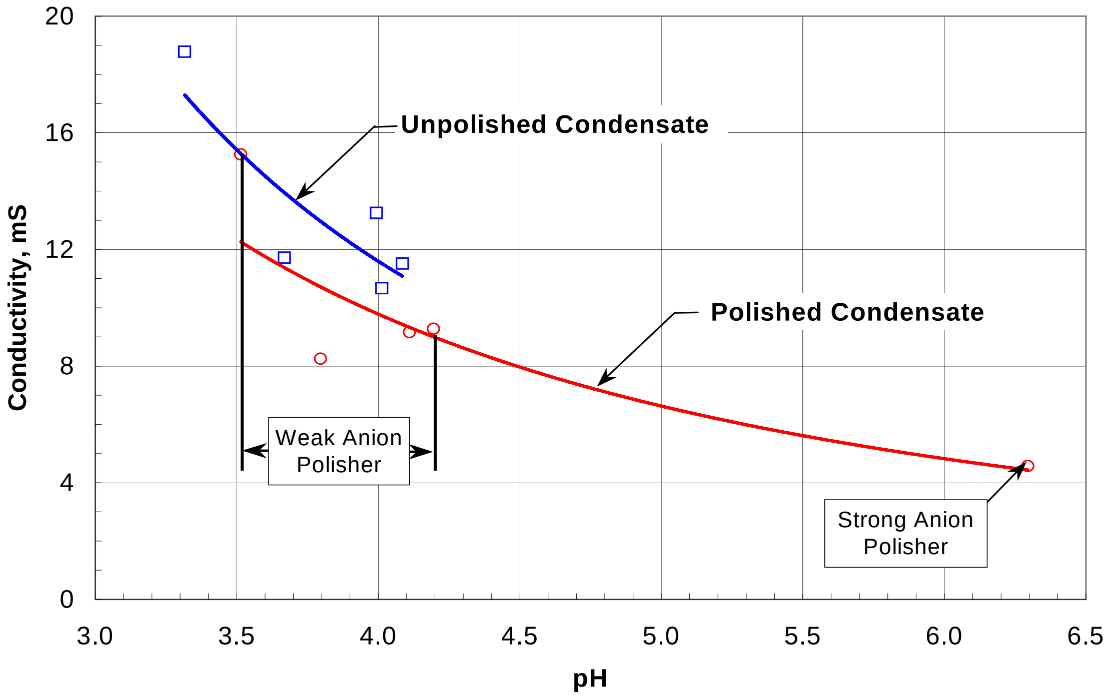


Figure 13. Conductivity and pH of Condensate before Polishing and after Polishing with Weak or Strong Anion Resins

In all cases the condensate polishers used a strong-cation resin in the H^+ form and normally used a weak-anion resin in the OH^- form to minimize removal of the weak bicarbonate (HCO_3^{--}) and carbonate (CO_3^{-2}) anions. With the strong-cation/weak-anion resin combination, the condensate polishing process caused the pH to increase only about 0.15 units on average (a reduction in acidity by a factor of ~1.4) and the conductivity to decrease by a factor of ~1.3 on average. When the strong-cation and weak-anion polishing resins became spent (i.e., no longer effective), the pH of the condensate decreased slightly (~0.25 units, a reduction in acidity by a factor of ~1.8) but the conductivity increased by a factor of ~4.

On one occasion, the vender inadvertently supplied a strong-anion exchange resin rather than a weak-anion resin. In that case, the strong-anion resin replaced most of the HCO_3^{--} and CO_3^{-2} anions with OH^- ions, causing the pH of the polished condensate to increase about 2.3 units (a reduction in acidity by a factor of ~200) and the conductivity to decrease by a factor of ~2. This behavior is displayed in Figure 13 and clearly shows a strong-anion resin to be effective in making the condensate less acidic; however, the resin became spent very quickly. Because strong-anion resins would require frequent regeneration and concomitant production of regeneration wastes, their use for polishing condensate in this application is considered to be inappropriate.

Table 4.
Conductivity and pH of Condensate

Date	Time	Power, %	Condensate pH	Condensate Cond., mS	Polisher Effluent pH	Polisher Effluent Cond., mS	pH Change
Polisher with fresh, weak anion exchange resin							
12/14/05	1245	35	3.28	17.10	3.57	11.40	0.29
12/20/05	1130	35	3.72	17.90	3.80	14.30	0.08
1/2/06	1330	35	3.20	18.30	3.30	15.60	0.10
1/3/06	1330	35	3.18	18.60	3.50	16.50	0.32
1/5/06	1330	35	3.20	22.00	3.40	18.50	0.20
Average		**35**	**3.32**	**18.78**	**3.51**	**15.26**	**0.20**
3/1/06	1245	40	3.83	12.79	4.06	10.01	0.23
3/1/06	1345	40	4.12	13.47	4.05	9.35	-0.07
3/1/06	1445	40	4.03	13.50	4.22	8.13	0.19
Average		**40**	**3.99**	**13.25**	**4.11**	**9.16**	**0.12**
3/1/06	1545	50	4.17	11.39	4.21	9.35	0.04
3/1/06	1645	50	4.00	11.64	4.18	9.21	0.18
Average		**50**	**4.09**	**11.52**	**4.20**	**9.28**	**0.11**
3/7/06	1130	60	3.74	12.78	3.74	10.31	0.00
3/7/06	1230	60	3.64	10.94	3.81	8.36	0.17
3/7/06	1330	60	3.62	11.85	3.81	7.56	0.19
3/7/06	1430	60	3.62	10.86	3.76	7.36	0.14
3/7/06	1530	60	3.72	12.15	3.86	7.66	0.14
Average		**60**	**3.67**	**11.72**	**3.80**	**8.25**	**0.13**
Overall Avg		**46**	**3.67**	**14.35**	**3.82**	**10.91**	**0.15**

Date	Time	Power, %	Condensate pH	Condensate Cond., mS	Polisher Effluent pH	Polisher Effluent Cond., mS	pH Change
Polisher with spent, weak anion exchange resin							
11/29/05	1200	33	2.81	44.50	2.89	43.90	0.08
11/29/05	2200	33	3.31	47.20	2.79	46.10	-0.52
11/30/05	1100	33	3.10	52.30	3.20	53.70	0.10
11/30/05	2200	33	2.98	46.11	2.90	55.10	-0.08
12/1/05	1030	33	3.03	58.20	3.20	60.50	0.17
12/1/05	2215	33	3.66	61.80	3.70	62.50	0.04
12/2/05	1100	33	3.20	64.30	3.60	65.70	0.40
1/27/06	1300	30	2.98	58.00	2.90	55.00	-0.08
1/31/06	1300	35	2.74	58.90	2.76	66.00	0.02
2/1/06	1230	35	3.50	65.00	3.40	72.00	-0.10
2/7/06	1330	30	2.81	70.00	2.90	73.00	0.09
2/8/06	1300	35	2.75	77.40	2.72	79.00	-0.03
Average		**33**	**3.07**	**58.64**	**3.08**	**61.04**	**0.01**

Polisher with strong anion exchange resin							
2/14/06	1315	60	3.95	11.78	6.47	6.25	2.5
2/14/06	1410	60	4.18	10.57	5.99	3.21	1.8
2/14/06	1505	60	3.91	10.61	6.36	4.47	2.5
2/14/06	1602	60	4.01	9.72	6.36	4.36	2.4
Average		**60**	**4.01**	**10.67**	**6.30**	**4.57**	**2.28**

The slightly acidic condensate can easily be handled by the use of corrosion resistant materials (Inconel, stainless steels, CPVC). The pH level reaches a self-limiting value based on the saturation level of CO_2 in the condensate and does not decrease further. Attempting to neutralize the pH only adds chemicals to the system, increases maintenance costs and man hours, and potentially introduces high-temperature “plating out” problems through the introduction of specious chemicals into an otherwise very pure system of de-ionized condensate water.

3.7 Inspection of Gas Generator, Steam Piping, and Turbine

Periodically throughout the testing, the GG and turbine were visually inspected remotely using a video borescope and by disassembly for direct visual examination for erosion and/or corrosion. The steam pipes were inspected in areas adjacent to valves and steam traps where access was most readily possible.

3.7.1 Gas generator inspections

The GG received the most frequent inspections as it was subjected to higher temperatures, pressures, and excess O_2 concentrations than the rest of the steam system. Inspections were conducted at one- to two-week intervals until operational experience allowed for longer intervals between inspections. Both borescopic and direct visual inspections were conducted, with borescopic inspections primarily utilized when maintenance downtime was insufficient to permit GG disassembly.

In general, the GG exhibited little wear over the durability demonstration. Within the GG, the main injector and combustion chamber are exposed to the most extreme conditions, with the highest metal surface temperature measured at 734°F. Nonetheless, both components appeared almost pristine over an operating period of more than 1,300 hours, exhibiting primarily superficial heat marks during each inspection. Photographs of internal surfaces of the GG after extended durability testing are shown in Figure 14. The face of the main injector after 1,050 hours of operating time is shown in the left photograph. Discoloration (heat marks) is evident but no surface damage was discernible. The appearance of the inner bore of the GG after 1,190 operating hours is shown in the right photograph. The perspective in the photograph is looking from the aft end of the third cooldown chamber forward toward the fingered diluent injector at the entrance of the first cooldown chamber and beyond to the main injector. Superficial heat marks are visible on the inner walls of the combustion and cooldown chambers, but the walls are otherwise smooth and shiny. The rest of the GG fared similarly well, with four exceptions as described in the following paragraphs.

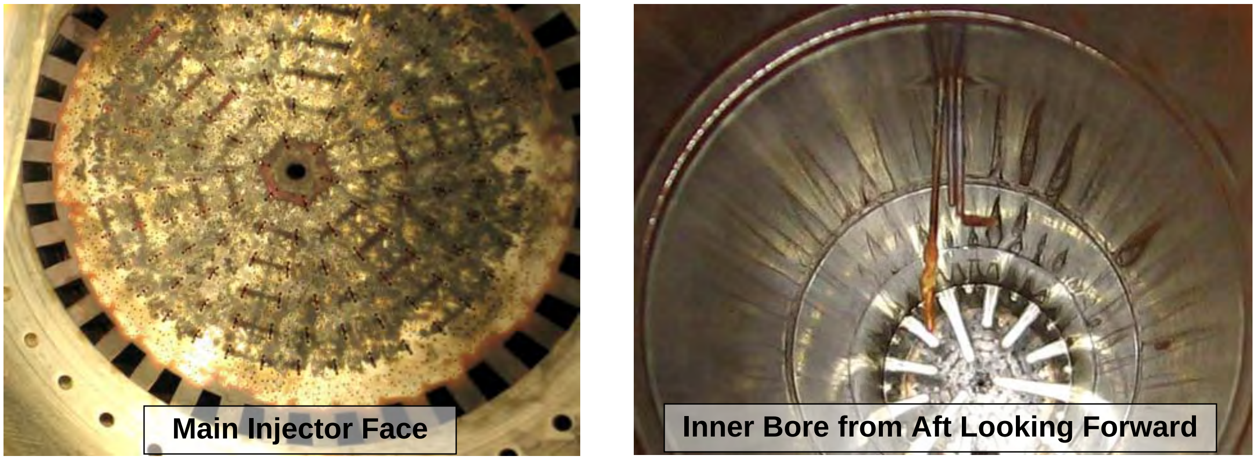


Figure 14. Gas Generator Internal Surfaces after Extended Durability Testing

- **Aft flow restrictor/diluent injector.** This component, along with a downstream orifice, served in a previous testing effort as a restriction to simulate the pressure drop a turbine would impose (i.e., as a turbine simulator). The contoured inlet to this component was cooled by water injection at the periphery of the throat. In this test program, the "turbine simulator" was used without the downstream orifice at the GG exit to reduce the drive gas pressures to a level more compatible with the KPP steam turbine. The water-injection-cooling feature was used along with the fourth diluent injector to control the temperature of the drive gas exiting the GG. However, this component had a copper injection section that was gradually corroded by the acidic condensate passing through and over it. In the previous test program, this section was exposed only to non-acidic deionized water. The corrosion was discovered during a routine inspection and the component was renovated by substituting an Inconel section for the copper one. No further corrosion was observed. Corrosion of copper by acid condensate was known and its presence in this component was an oversight.
- **Combustion chamber coolant diverter manifold.** The GG, as originally designed, utilized full regenerative cooling to capture heat transferred to the GG cooling water by injecting the cooling water back into the GG via the main injector and the diluent water injectors at the front of each cool-down chamber. From lessons learned in an earlier test program, CES changed the GG cooling water flow circuits to provide continuous, more controllable wall cooling of the combustion chamber. This was accomplished by adding a coolant diverter manifold at the front of the combustion chamber. Mid-way through GG durability testing, a flaw in the inner liner of the coolant diverter manifold resulted in a crack through which additional cooling water (recirculated condensate) was injected into the combustion chamber during operation. Because the crack was hidden from view during borescopic inspections and the DCS automatically compensated for the additional injection water by reducing water flow through downstream diluent injectors (i.e., the GG continued to perform normally), the problem was not discovered until data

analysis showed less water was being injected through the diluent injectors controlling the exit gas temperature than expected, and CO levels were elevated. Cold flow tests and a tear-down inspection isolated the problem and the diverter manifold was removed for repair. Following replacement of the inner liner, the manifold was placed back in service and no further problems have occurred. In the new baseline GG design, continuous wall cooling for the combustion chamber is accomplished without the need for a coolant diverter manifold.

- **Combustion chamber coolant inlet.** The combustion chamber coolant inlet manifold performed satisfactorily throughout the entire period of the durability testing. However, inspection revealed hot corrosion at the inner lip of the sealing surface late in the first year of operation. Though not extensive enough to warrant repair, this component of the GG was closely monitored during the later inspections. Thermal analyses indicate this manifold is the hottest area in the GG. New baseline GG designs will eliminate this "hot corrosion" problem by eliminating this separate coolant inlet manifold (and its attendant seals and constrained cooling passages) by incorporating coolant inlet and outlets into the flanges of the GG barrel sections. Wall cooling in the flanges is also improved by better cooling passage design. The two design modifications are anticipated to eliminate the local conditions contributing to hot corrosion.
- **GG seals.** Durability testing over the period of months revealed a weakness in seals between the various sections of the GG. These seals were selected based on good experience under the severe conditions of pressure and temperature encountered in rocket propulsion systems, albeit for short periods of times. The problem was embrittlement caused by sustained exposure to heat and pressure. After weeks or months of operation, the GG water seals began leaking. Although seal replacement temporarily cured leakage, the new seals eventually also leaked. Several alternative seals were tried with the same result (i.e., the seals began leaking after a period of satisfactory performance). This was unsatisfactory both from a seal perspective and the additional GG maintenance this caused. Eventually Garlock Helicoflex seals were tried. These seals feature spiral-wound stainless steel that is plated with a silver alloy and provide long-term resilience at high pressures and temperatures. The Garlock seals have performed well with no leaks since they were installed, and have been in use for 341 hours of the 1,333 hours of GG operations described in this report.

3.7.2 Steam turbine inspections

The steam turbo-generator (STG) was inspected prior to the initiation of GG operations. The turbine blades, bearings, and mechanical control mechanisms were found to be in very good condition. The steam path was relatively clean, but some scale was observed in the steam feed lines and turbine manifold. High pressure steam cleaning removed most of this scale.

- During the initial GG testing, the deionized water and condensate filters required frequent cleaning due to rapid rust accumulation. Gradually the high quality steam and DI water flushed the system, rust accumulation diminished, and filter change frequency dropped significantly. Most of the rust came from pre-existing conditions in the steam lines (primary source) and STG (secondary source). Each successive STG inspection showed a cleaner turbine and steam path. After six months of operation, the STG was pronounced to be "clean as a whistle."

- The KPP STG was designed to operate on steam rather than GG drive gases that contain a significant amount of non-condensable CO_2 and cause the condensate to be slightly acidic. Nevertheless, GG drive gases at temperatures above the saturation point did not adversely affect STG operations.
- The only adverse effect of the GG on STG operations occurred during extended periods of non-operation. Due to the tendency of an otherwise dry STG to condense high humidity gases left in the system, rust accumulated inside the STG during downtimes longer than 24 hours unless the system was thoroughly dried immediately after each STG shutdown. Drying was easily accomplished by operating the condenser's liquid ring vacuum pump for 30-45 minutes at the end of each operating session.

3.7.3 Steam pipe inspections

Steam pipes used in a CES cycle would normally be constructed of stainless steel due to the corrosive, acidic nature of the condensate that could form during turbine startup and after shutdown. Since the existing KPP piping system was constructed of carbon steel, special emphasis was focused for corrosion monitoring. Access to internal steam piping was, however, limited to locations adjacent to valves and traps. The steam lines immediately down stream of the GG were inspected twice a month, and at the steam trap near the inlet to the STG at three month intervals when corrosion coupons were installed and removed.

- It is well known that carbon steel corrodes in the presence of acidic water. Extended operations with steam/CO_2 drive gas at temperatures above the saturation point reduced but did not eliminate steam pipe corrosion. The steam pipes tended to be very clean internally after extended runs. However, short duration runs and down time between runs with damp steam pipes resulted in noticeable corrosion as evidenced by rust formation.
- The thickness of the steam piping was measured immediately before and after the corrosion coupons were installed and tested. The original pipe thickness decreased 0.005 to 0.007 inches in a calendar period of 213 days and 885 operating hours. This indicates an annual erosion of about 50 to 70 mil/yr based on operating hours, or about 9 to 12 mil/yr based on calendar time. The former values agree quite well with the coupon corrosion data discussed in Section 3.8 and listed in Table 5 for A106B carbon steel at the turbine inlet.

3.8 Installation And Periodic Inspection Of Corrosion Test Coupons

Corrosion test specimens were installed in the Kimberlina Power Plant in two locations: (1) near the inlet to the steam turbine and (2) in the mid-section of the condenser. Duplicate specimens of three austenitic stainless steels (304H, 304L, and 316L) and one carbon steel (A106B) were exposed for nominally 600 hours to the operating environment at the respective locations during a calendar period of 91 days. The nominal volumetric composition of the gas stream entering the turbine and condenser was ~90% steam, 9% CO_2, and 1% O_2. The operating temperatures and pressures at the turbine inlet were ~650°F and 650 psig and at the condenser-midsection ~103°F and 10 inches Hg vacuum (4.9 psia = -9.8 psig).

The corrosion data for all of the test specimens in each location are summarized in Table 5 and graphically displayed in Figure 15. The tabular data include average corrosion rates (mils/yr) and maximum pit depth (mils) where applicable. No pitting was observed in the stainless steels at condenser operating conditions, but pitting was seen in the carbon steel specimens in both test environments, and in both stainless steels that were examined for pitting behavior when exposed to turbine inlet conditions. The average corrosion rates for the stainless steel specimens ranged from 3.45 to 5.66 mils/yr and from about 0.97 to 1.3 mil/yr at turbine inlet and condenser operating conditions, respectively, whereas the carbon steel corroded at rates of about 60 and 52 mils/yr in the corresponding environments.

Table 5.
Corrosion of Test Specimens in Steam/CO_2/O_2 Atmosphere at Kimberlina Power Plant

Turbine Inlet			
Test Specimen		Corrosion Rate	
Alloy Material	Spec. ID	Avg. mil/yr	Max. Pit Depth, mil
316L	A5091	3.62	5.9
316L	A5092	3.29	Undefined
	Average	3.45	
304L	B2756	4.17	Undefined
304L	B2757	4.77	6.3
	Average	4.47	
304H	03	6.43	Undefined
304H	04	4.89	Undefined
	Average	5.66	
A106B	03	59.0	7.3
A106B	04	61.9	Undefined
	Average	60.5	

Condenser Mid-section			
Test Specimen		Corrosion Rate	
Alloy Material	Spec. ID	Avg. mil/yr	Max. Pit Depth, mil
316L	A5089	1.285	None
316L	A5090	1.308	None
	Average	1.297	
304L	B2754	1.110	None
304L	B2755	0.987	None
	Average	1.049	
304H	01	0.998	None
304H	02	0.936	None
	Average	0.967	
A106B	01	48.6	5.7
A106B	02	55.1	Undefined
	Average	51.9	

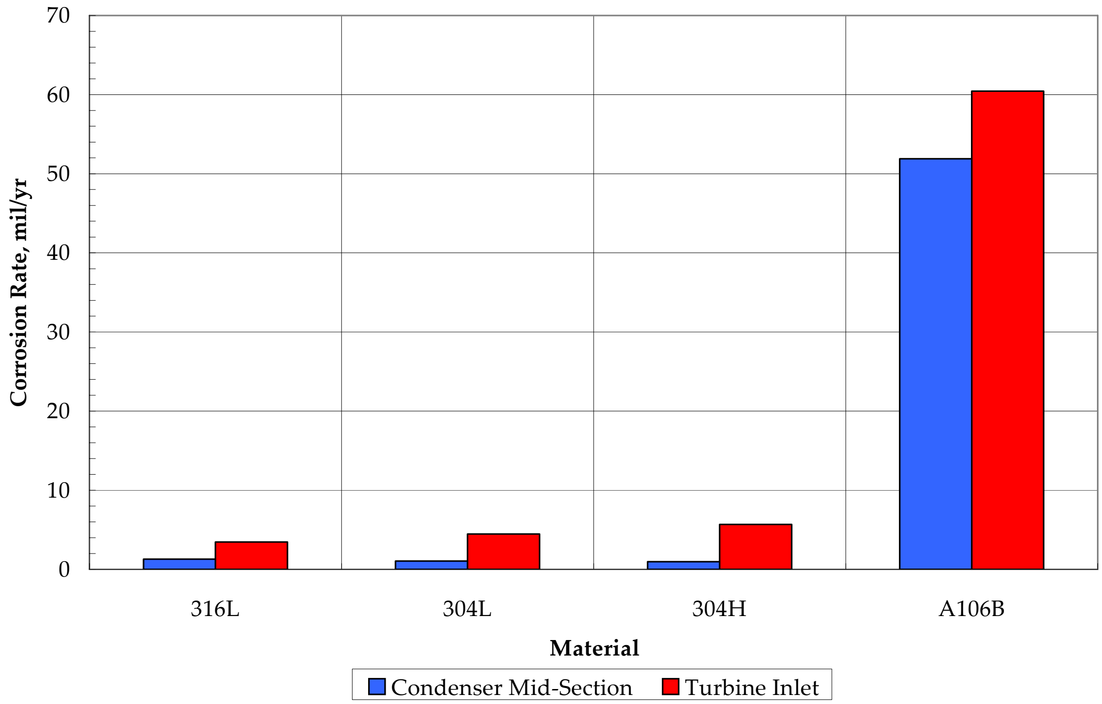


Figure 15. Corrosion Rate of Materials in Steam/CO_2/O_2 Atmosphere

Pictures of the test specimens exposed to GG drive gases at the condenser mid-section are shown in Figure 16 and another three of the eight specimens exposed to the drive gases at the turbine inlet are shown in Figure 17. In each of these figures the three specimens at the top of the figure show the front and backsides of the test coupons after exposure to the drive gases but prior to cleanup. Similar views of the same coupons are shown in the bottom portion of each figure after cleanup.

All of the coupons prior to cleanup have a rusty appearance. In the case of the stainless steel specimens, the rusty coatings were superficial and apparently deposited on the surfaces by particles of entrained rust from upstream sources. In contrast, the carbon steel specimens prior to cleanup were not only rusty in appearance but also were covered with a very noticeable loose scale of corrosion products (i.e., rust).

After cleanup of the specimens, all the coupons exhibit a normal metallic luster. However, the stainless steel specimens all exhibit smooth-appearing surfaces, while the carbon steel specimens exhibit obvious rough pitted surfaces, indicative of significant corrosion.

These corrosion tests clearly establish the desirability of using stainless steel rather than carbon steel for components exposed to the GG drive gases and potential acidic condensate produced during startup and shutdown operations. This limited testing suggests that 316L is somewhat preferred over 304L or 304H stainless steels in higher temperature, higher pressure drive gas exposures, such at drive gas piping, but 304H or 304L is slightly preferred over 316 SS for the milder condenser operating conditions.

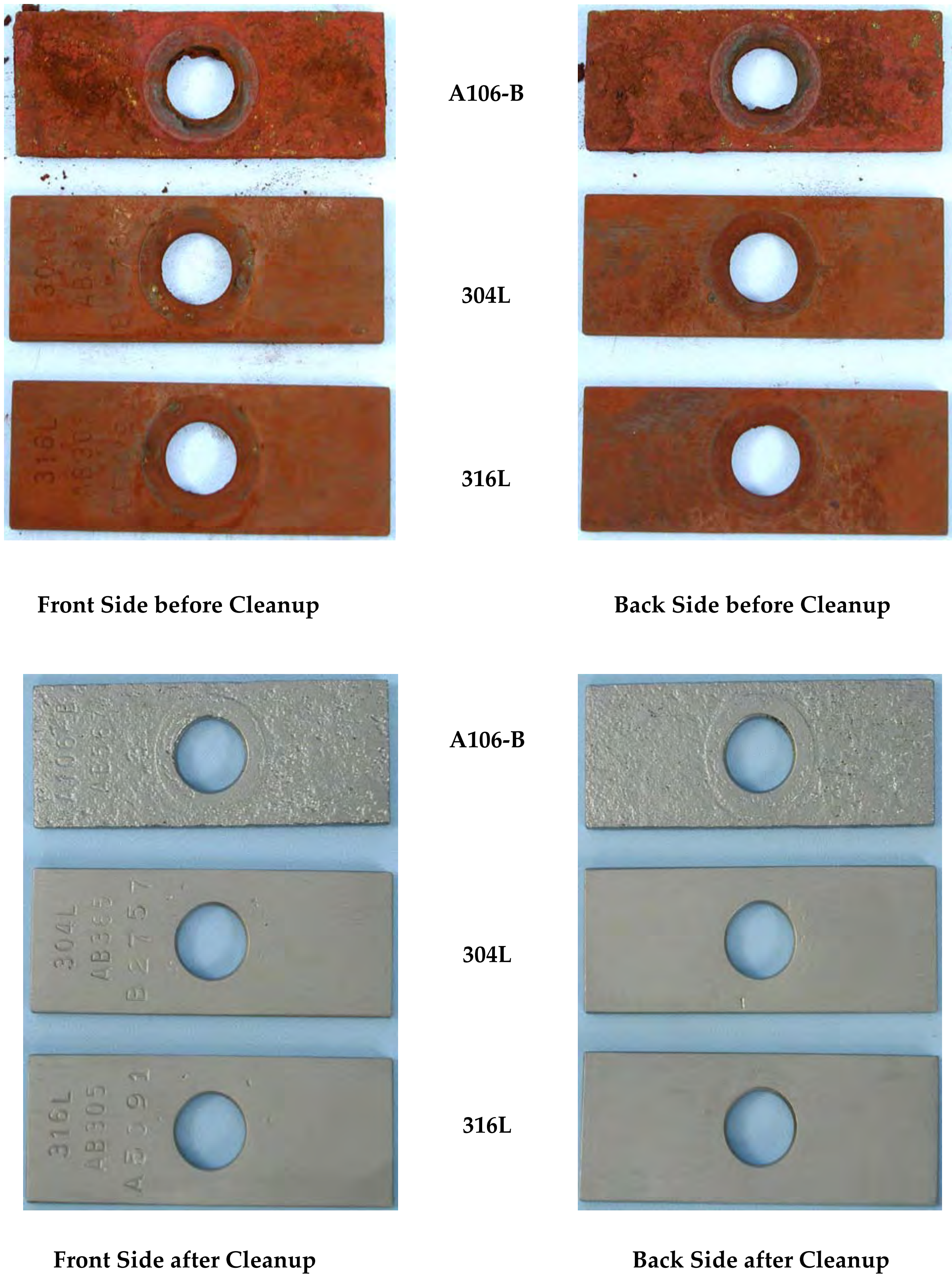
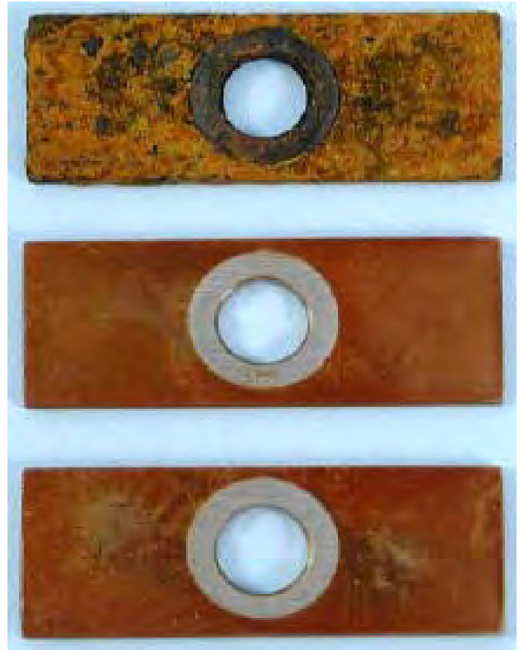


Figure 16. Corrosion Specimens at Condenser Mid-Section

A106-B

316L

304L



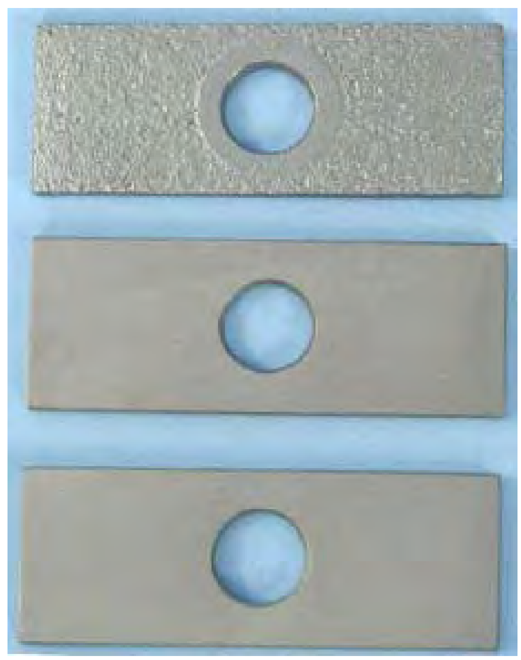
Front Side before Cleanup

Back Side before Cleanup

A106-B

316L

304L



Front Side after Cleanup

Back Side after Cleanup

Figure 17. Corrosion Specimens at Turbine Inlet

4.0 Conclusions and Recommendations

4.1 Conclusions

The gas generator and its digital control system, along with the various new supporting subsystems, were successfully turned over for routine operation in February 2005. Power was first exported to the grid on 28 February 2005 and the power plant was fully commissioned in June 2005. The GG proved reliable, easy to start, and was easily controlled.

The controls for the GG system were refined and adjusted in the course of the commissioning and durability demonstration efforts in a number of ways. Significant refinements and adjustments were made in four broad categories: (1) data acquisition, (2) sequencing and kill parameters, (3) control loops, and (4) human machine interface (HMI).

Long-term durability tests generally occurred during the period from 28 February 2005, the first export of power to the grid, through 29 March 2006 and run numbers 31 through 413. Over the course of all the testing, the GG was started ~300 times (i.e., achieved at least 20% of full power) and accumulated a total of 1,333 hours of operating time. Individual test runs ranged from less than one minute to approximately 105 hours. Power levels ranged from 20% to 88% of full power during almost 1,333 hours of GG operation. Power was exported to the electrical grid at power levels from 0.5 to 2.7 MW_e during 141 runs encompassing 1,243 hours of GG operation. The GG operated continuously for periods longer than eight hours in 43 of these runs, covering a total of 817 hours of operation, and for periods greater than 24 hours in 11 runs totaling 445 operating hours.

Ninety-four tests of greater than four-hour duration each and covering a total of 1,123 hours of GG operation (84% of total operating experience) were performed under this program. Of those 94 tests, only 10 were terminated because of a GG system fault, and five of those were terminated by the operator to repair simple water leaks. Since the end of the GG system commissioning effort on 6 June 2005 (Run 131), only two tests were automatically terminated because of GG system faults during 76 tests of greater than four-hour duration each and 1,014 hours of operation.

Measured CO emissions at 50% power, expressed in terms of pounds of CO per million Btu, ranged from ~0.02 to 0.31 over a wide range of GG system operating conditions. For comparison with gas turbines, CO emissions ranged from ~5 to 80 ppmv, corrected to 15% O_2. The emissions of CO tend to increase when the GG system is operated at higher power levels. Measured NO emissions at 50% power, expressed in terms of pounds of NO_2 per million Btu, ranged from ~0.003 to 0.019, and ranged from ~0.3 to 4.0 ppmv, corrected to 15% O_2. These observed CO and NO_x emissions are considerably lower than the best observed in combined cycle power systems operating on natural gas, even with SCR for NO_x control. Strategies for further decreasing the emission of CO and NO_x from this first-generation GG system have been formulated and will be experimentally evaluated in future testing efforts. Unburned hydrocarbon emissions for two different operating stoichiometries were ~0.9 and 1.8 ppmv when corrected to 15% O_2.

Changing the first diluent injector in the GG from an edge-spray to fingered type improved the radial mixing and smoothed the radial temperature profile in the drive gas. The effects of power levels, injection water-to-oxygen mass ratios (W_i/O_2), and excess oxygen concentrations on temperature profiles with the fingered diluent in place, were also determined. The diminished "hot core" characteristic produced by the fingered injector is highly desirable and favors that design approach for future GG systems.

The conductivity and pH of the condensate was measured as directly recovered from the condenser, and after polishing via strong-cation/weak-anion ion exchange beds, when operating the power plant under various conditions. The polishing process caused the pH to increase on average from ~3.67 to 3.83 (a reduction in acidity by a factor of ~1.4) and the conductivity to decrease on average from 14.35 to 10.91 mS (a factor of ~1.3).

Periodically throughout the testing, the GG and turbine were visually inspected remotely using a video borescope and by disassembly for direct visual examination for erosion and/or corrosion. The GG exhibited little wear over the durability demonstration. The main injector and combustion chamber appeared almost pristine over an operating period of more than 1,300 hours, exhibiting primarily superficial heat marks. The turbine blades, bearings, and mechanical control mechanisms were initially found to be in very good condition and each successive STG inspection showed a cleaner turbine and steam path. From wall thickness measurements, the corrosion rate of the carbon steel piping was found to range from 50 to 70 mil/yr based on 885 operating hours or about 9 to 12 mil/yr based on 213 calendar days.

Corrosion test specimens for three austenitic stainless steels (304H, 304L, and 316L) and one carbon steel (A106B) were exposed for nominally 600 hours to the operating environment near the inlet to the steam turbine and in the mid-section of the condenser during a calendar period of 91 days. The average corrosion rates for the stainless steel specimens ranged from 3.45 to 5.66 mils/yr and from about 0.97 to 1.3 mil/yr at turbine inlet and condenser operating conditions, respectively, whereas the carbon steel corroded at rates of about 60 and 52 mils/yr in the corresponding environments.

4.2 Commercial Potential

The excellent reliability exhibited by the CES GG and DCS during durability testing indicates they are ready for commercial deployment for power generation. This section describes the commercial system to be provided by CES and the extent to which components of this system are ready for commercial manufacturing and production.

4.2.1 Gas generator system

For installation in a commercial power plant, the CES GG will be shipped as a pre-assembled gas generator subsystem (GG subsystem). The GG subsystem will be connected to gaseous fuel,

O_2, and DI water from power plant subsystems. Some plant subsystems may be integrated with the GG subsystem to improve power plant efficiency. Systems integration will be decided on a case-by-case basis, with increased capital costs and plant complexity balanced against decreased operating costs. The GG subsystem will normally include:

- GG (including ignition system);
- DCS and instrumentation systems;
- Mounting frame ("bench");
- O_2 piping, including filters, shutoff valves, flow control valves, check valves, flow control devices (orifices and venturis), and instrumentation;
- Fuel supply lines, including filters, shutoff valves, flow control valves, check valves, other flow control devices (orifices and venturis), and instrumentation (pressure, temperature, and flow sensors);
- Instrument air system, including filters, supply and actuator lines, shutoff valves, check valves, pressure control valves, and pressure sensors;
- Purge gas (N_2) system, including filters, supply and purge lines, shutoff valves, check valves, pressure control valves, and pressure sensors;
- DI water system, including filters, supply lines, shutoff valves, flow control valves, check valves, other flow control devices (orifices and venturis), and instrumentation;
- Local control panel;
- Wiring harnesses; and
- O_2 leak and NG leak sensors.

4.2.2 Critical production processes

CES is not a direct manufacturer of all GG subsystem components, but subcontracts to pre-qualified suppliers and vendors, including GG manufacturing. CES conducts and controls project management, engineering, quality control, final assembly, testing, installation, GG commissioning, business development, and marketing. The manufacturing risks for the GG subsystem were all deemed low. Primary GG elements include:

- **Main injector**—composed of a nickel alloy manifold body to which individual chemically-etched platelets are diffusion bonded,
- **Combustor and cool down chambers**—comprised of identical high strength nickel alloy spool bodies and liner inserts, and
- **Diluent injectors**—consisting of platelet injector "fingers."

The commercial design is a refinement of the KPP GG and will have common, interchangeable combustion and cool down chambers. This reduces production costs and spares inventories. Production GG chambers will be constructed of the same high-nickel alloys used in the prototype unit. All required fabrication steps were demonstrated during construction of the GG prototype—no new manufacturing techniques are involved. The larger GG internal diameter required for higher power (from four to as much as 12 inches) poses no manufacturing risk as existing machine tools (lathes, drill presses, mills, etc.) and joining methods (diffusion bonding, brazing, and welding) accommodate GG assemblies of this size.

CES evaluated GG technical risks as low. The technical risks include:

- **Combustion stability**—the GG uses acoustic cavities to suppress likely modes of combustion instability and extensive testing has not indicated any sign of instability. Production units will employ similar features, though the cavity design will change slightly to suppress the "most probable" frequencies of possible instability in larger diameter combustion chambers.
- **Wall cooling**—wall cooling has been satisfactory so CES plans to continue with the current design approach. Minor changes will be made in the cooling water pathway in the vicinity of GG joints to minimize hot spots and reduce the number of seals.
- **Drive gas mixing**—"fingered" diluent injectors will be used in lieu of "edge spray" injectors. During GG testing, finger injectors distributed injected DI water more uniformly than edge sprays and substantially reduced downstream temperature differences between the GG core and side walls.

GG subsystem manufacturing and technical risks were also evaluated as low. They include:

- Bench assembly—benches will be longer, wider, and higher to facilitate GG subsystem maintenance. Standard metal fabrication and welding techniques will be used.
- Gas supply system—O_2 and NG supply lines, filters, instrumentation, and valves will be manufactured from standard designs and materials. Special attention is required for O_2 cleanliness requirements, but this is well understood. Instrumentation and purge gas systems are likewise well understood.
- Control system—the control panel utilizes standard cabinets. Wiring harnesses will be pre-fabricated to reduce GG subsystem installation time and permit thorough factory testing for wiring errors before the GG subsystem is shipped to the installation site.
- Leak sensors—depending on local code requirements, CES will utilize off-the-shelf leak sensors as baseline GG subsystem equipment to detect fuel and O_2 leakage in the vicinity of the GG bench. Off-the-shelf sensors will be used for this function.

4.2.3 Capacity constraints

No production capacity constraints are envisioned except for control and shutoff valves. Long lead-times associated with large valves caused CES to evaluate capacity risk as medium.

- O_2-rated valves—although valve designs are relatively standardized, two factors add lead-time to the acquisition of O_2 service valves. The first is that most large capacity O_2 valves are built only to order—that is, there is no inventory maintained. A typical O_2-rated valve's lead-time is six to nine months. In addition, some materials involved in O_2 valve fabrication have their own lead-times (e.g. Monel valve seats, trim, valve bodies).
- Large valves—larger valve sizes are generally not stockpiled and manufacturing lead times of up to six months must be taken into account.

4.2.4 Hazardous materials

No known hazardous materials are used in the manufacturing process of the GG or its control system and only environmentally acceptable O_2 cleaning solvents are utilized. Some hazardous materials are utilized in photo etching, machining (cutting oil) and welding/joining (acetylene, O_2, fluxes, brazing materials) processes, but their use and control thereof are well understood and accommodated by responsible vendors and CES personnel. Manufacture of the CES GG will not introduce new process hazards nor generate unique waste products. All CES vendors have approved environmental hazard control processes in place.

4.2.5 Projected cost

Production costs of the CES GG subsystem will vary with combustor size, content of the bench (valve and sensor types and sizes), the size of the production run, and its similarity to previous GG designs. In general, the cost of the GG subsystem will be between 5% and 10% of the total power plant cost. Initial customer cost for a 170 MW_t, natural gas-fired GG with typical bench components and control system would be approximately $8,000,000. This size combustor would produce approximately 50 MW_e with existing turbo-generators at a total plant cost of approximately $100 million.

4.2.6 Investment threshold-to-launch

CES believes that its first commercial product could be launched with an additional investment of $2,000,000, which is required to increase staff capabilities for project management and control. These funds have been obtained, so there are no expected financial obstacles to deploying CES technology. CES currently leases 6,000 square feet in Rancho Cordova, CA, which is sufficient to meet expected product sales over the next three years.

4.2.7 Implementation plan to reach full production

CES has defined the following approach to build up to full production. The schedule is largely dependent on CES' first commercial project, currently in development:

1. Engineering services commercial contract (170 MW_t GG) (GG-1)—September 2005 (accomplished)
2. DOE syngas combustor (GG-S) development award—September 2005 (accomplished)
3. Issue R&D Implementation Plant for GG-S—March 2006
4. Issue detailed GG-1 design (170 MW_t)—April 2006
5. Go-ahead for GG-1 manufacturing + plant design—April 2006
6. Begin fabrication of GG-1—July 2006 to October 2006
7. Preliminary design issued for pre-commercial GG-S—August 2006
8. Begin detailed design of pre-commercial GG-S—October 2006
9. Complete GG-1, begin factory acceptance testing—July 2007
10. Issue detailed design of pre-commercial GG-S—January 2007

Assumptions: The implementation plan assumes one GG subsystem sale in 2006, one or two GG subsystem sales/year during the following two or three years, and two or three annual sales thereafter. GG subsystem factory acceptance testing will be conducted at the Kimberlina facility. Control system design is included in the detailed GG-S design.

4.3 Recommendations

- Conduct additional GG durability testing under modified operating conditions to demonstrate further reductions in NO_x, CO, and hydrocarbon generation.
    - **CES Implementation Plans**: Reductions in NOx and CO are desirable to support the peaker plant application, where the exhaust gases are vented to atmosphere. CES will conduct additional tests to vary the distribution of water in the injector and combustion chambers to minimize creation of NOx and CO.
- Conduct GG demonstration testing with simulated and coal-derived synthetic gas (syngas) to validate combustor compatibility with the lower heating value of syngas and particulate contamination.
    - **CES Implementation Plan:**
        - In April 2006, CES installed a blending station at the Kimberlina facility to permit on-site creation of simulated syngas from constituent gas elements
        - CES modified fuel and O_2 delivery systems for the GG at Kimberlina Power Plant to permit low power testing of the GG operating on syngas
        - CES will conduct six weeks of syngas testing beginning 9 June 2006
        - CES will manufacture a 4-inch main injector specifically designed for syngas oxy-fuel ratios, and will conduct an additional 4-6 weeks of syngas testing with the new main injector
        - CES will investigate the feasibility of relocating the syngas gas generator to an existing gasification facility for longer term endurance testing.
- Conduct combustor compatibility testing with gas turbines to demonstrate its utility in ultra-low emission "peaker" plants.
    - **CES Implementation Plan:**
        - CES is currently designing a peaker power plant utilizing a 134 MW_t CES GG driving a modified J79 aircraft turbine and a lower pressure exhaust turbine, each connected to an electrical generator.
        - A CES-cycle peaker power plant offers lower capital cost and two to three times the equivalent gas turbine power output (because the gas turbine compressor is not used), albeit at higher operating expense.
        - CES is seeking preliminary commercial/demonstration sites in California.

4.4 Benefits to California

- The Kimberlina Zero-Emission Power Plant demonstration illustrated the exceptional reliability, durability, maintainability, and usability (RAMDU) of the CES GG over a 15-month operating period. The demonstration proved GG RAMDU in the most convincing manner possible—in an operating power plant while exporting power to the electricity grid. It also demonstrated that a technology exists for zero-emission electrical power generation from gaseous fossil fuel.

- Successful testing at Kimberlina Power Plant resulted in the insurance industry providing full commercial insurance coverage for the CES gas generator. This was not available at the outset, and directly resulted from this Energy Commission-funded demonstration project. Insurability of equipment is key to subsequent commercial deployment.
- Future GG demonstrations will prove its zero-emission capabilities and effectiveness with low-heating value gaseous fuels (e.g. landfill gas or anaerobic digester gas) and gasified solid carbonaceous fuels (e.g. biomass, coal, petcoke).
- This proven technology is now ready for use in:
    - Base-load, zero-emission power plants with efficient CO_2 capture, making them "climate neutral"
    - Peaker power plants with ultra low emissions
    - Power production combined with the gasification of liquefied natural gas (LNG)
    - Thermal desalinization and power production
    - Power generation combined with enhanced hydrocarbon (oil, natural gas, coal bed methane) recovery, when the captured CO_2 is used for this purpose.

  Although any of these applications would have justified the Energy Commission investment in this demonstration project, the matrix of capabilities of the CES-cycle enables this technology to offer an extraordinary opportunity to simultaneously improve California's future energy supply, economy, and environment.
- In the near term, near-zero emission, affordable, peaker power plants are expected to become available to help stabilize California spot energy demand. CES is actively pursuing deployment of the first of these modular peaker units in southern California, where such power is most needed and emissions requirements are very strict..
- Base-load power plants using CES technology and incorporating CO_2 capture are expected to be first demonstrated in 50 MW_e plants located in The Netherlands and Norway in 2008-2010 timeframe. When located in California markets, these zero-emission power plants will not only produce abundant clean electrical power, but make available large quantities of compressed CO_2 for enhanced oil recovery (EOR). According to U.S. Department of Energy studies, CO_2 injection can recover more than five billion barrels of oil from existing California oil fields.
- The CES-cycle is also exceptionally well suited for use in gasifying LNG. A CES combustor could vaporize LNG for NG pipelines while also providing exportable electrical power, high-pressure CO_2, and pressurized N_2.
- The high thermal output of the CES-cycle makes it appropriate for thermal desalinization of water in coastal areas which need new sources of potable water.
- The flexibility of the CES-cycle enables it to deliver the promise of clean power through a variety of means—base-load, peakers, EOR—and meet the expanding energy needs of California's citizens.

5. Glossary

BACT	Best Available Control Technology
CDC	cooldown chamber
CES	Clean Energy Systems, Inc.
CFD	computational fluid dynamics (computer algorithm)
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CPVC	chlorinated polyvinyl chloride (chemical and heat resistant plastic piping)
DCS	digital control system
DI	de-ionized (water)
EISG	Energy Innovations Small Grant
EOR	enhanced oil recovery
GC-FID	gas chromatograph—flame ionization detector
GC-TCD	gas chromatograph—thermal conductivity detector
GG	gas generator, the name given to the CES oxy-fuel combustor
GG-1	170 MW_t gas generator
GG-S	gas generator operating on syngas
Hg	mercury
KPP	Kimberlina power plant
kW_e	kilowatts electrical
lb/MMBtu	pounds per million British thermal units
mil	0.001 inch
mS	milli-siemens
MW_e	megawatts electrical
MW_t	megawatts thermal
N_2	nitrogen
NG	natural gas
NO	nitric oxide
NO_2	nitrogen dioxide
NOx	nitrogen oxides
O_2	oxygen
peaker	power plant which operates under a limited duty cycle to supply power during periods of peak demand, hence a “peaker”
pH	a measure of the acidity or alkalinity of a solution (7 is neutral)
PIER	Public Interest Energy Research
ppmv	parts per million by volume
psia	pounds per square inch atmospheric
psig	pounds per square inch gauge (0 psig = 14.7 psia)
RAMDU	reliability, availability, maintainability, durability, and usability
RD&D	research, development, and demonstration
SCR	selective catalytic reduction
STG	steam turbo-generator
syngas	synthesis gas (synthetic gas derived from coal gasification)
VOC	volatile organic compound

Appendix A

Master Run Log

Run No.	Start Date	GG Output, %[†]	GG Output, MW_e	Run Time	Shutdown Comments	Shutdwn Cause
1	12/16/2004	20	0	0:02:38	Normal shutdown, test completed.	---
2	12/16/2004	20	0	0:01:00	Auto GG Trip, X5, index 16	GG Syst.
3	12/16/2004	20	0	0:06:13	Auto GG Trip, X5, index 37	H_2O Syst.
4	12/17/2004	20	0	0:23:06	Auto GG Trip, X5, index 37	H_2O Syst.
5	12/17/2004	20	0	0:06:30	Auto GG Trip, X5, index 4	GG Syst.
6	12/21/2004	20	0	2:46:40	Normal shutdown, test completed.	---
7	1/12/2005	20	0	0:01:11	Normal shutdown, test completed.	---
8	1/13/2005	20	0	0:01:17	Auto GG Trip, X5, index 2	GG Syst.
9	1/14/2005	20	0	0:00:50	Auto GG Trip, X5, index 2	GG Syst.
10	1/14/2005	20	0	0:10:00	Auto trip on oxygen skid	O_2 Syst.
11	1/15/2005	20	0	1:00:00	Normal shutdown, test completed.	---
12	1/16/2005	20	0	0:30:00	Normal shutdown, test completed.	---
13	1/17/2005	20	0	0:21:00	Auto GG Trip, X5, index 50	GG Syst.
14	1/18/2005	20-30	0	1:11:00	Auto GG Trip, X5, index 17	NG Syst.
15	1/24/2005	20	0	0:03:20	Normal shutdown, test completed.	---
16	1/25/2005	20	0	1:00:00	Normal shutdown, test completed.	---
17	2/3/2005	20	0	0:30:00	Auto GG Trip, X5, index 20	NG Syst.
18	2/3/2005	20-50	0	1:22:41	Normal shutdown, test completed.	---
19	2/4/2005	20-50	0	0:45:13	Auto GG Trip, X6, index 32	H_2O syst.
20	2/4/2005	20	0	0:00:51	Auto GG Trip, X5, index 32	H_2O syst.
21	2/8/2005	20-74	0	2:01:37	Auto GG Trip, X6, index 7	NG Syst.
22	2/8/2005	20-73	0	1:11:35	Auto GG Trip, X6, index 7	NG Syst.
23	2/9/2005	20-79	0	1:42:35	Normal shutdown, test completed.	---
24	2/14/2005	20-70	0	2:23:28	Normal shutdown, test completed.	---
25	2/16/2005	20-85	0	3:53:08	Auto GG Trip, X6, index 9	H_2O syst.
26	2/17/2005	25	0	0:04:54	Auto GG Trip, X6, index 11.	GG Syst.
27	2/17/2005	30	0	0:12:44	Auto GG Trip, X6, index 23	GG Syst.
28	2/17/2005	40	0	0:46:53	Auto trip on oxygen skid	O_2 Syst.
29	2/17/2005	35	0	0:24:38	Auto trip on oxygen skid	O_2 Syst.
30	2/25/2005	40	0	2:37:43	Normal shutdown, test completed.	---
31	2/28/2005	50	0.5	6:03:01	Normal shutdown, test completed.	---
32	3/1/2005	20	0	0:26:08	Normal shutdown, test completed.	---
33	3/3/2005	45	0.5	2:40:37	Auto trip on oxygen skid	O_2 Syst.
34	3/3/2005	45	0	0:35:59	Auto GG Trip, X6, index 22	GG Syst.
35	3/4/2005	55	0	1:48:07	Auto GG Trip, X6, index 22	GG Syst.
36	3/4/2005	65	1.1	0:59:28	Normal shutdown, elect. breaker problem	Elec. Syst.
37	3/8/2005	20-35	0.5	1:26:31	Normal shutdown to repair water leak	GG Syst.
38	3/8/2005	20	0	0:03:21	Auto GG Trip, X5, index 21	O_2 Syst.
39	3/8/2005	20	0	0:41:06	Auto GG Trip, X5, index 32	H_2O syst.

Run No.	Start Date	GG Output, %[†]	GG Output, MW_e	Run Time	Shutdown Comments	Shutdwn Cause
40	3/9/2005	20-55	0.5	3:38:11	Normal shutdown, elect. breaker problem	Elec. Syst.
41	3/10/2005	20	0	0:11:26	Normal shutdown to repair water leak	GG Syst.
42	3/10/2005	40	0.5	6:09:25	Auto GG Trip, X6, index 9	GG Syst.
43	3/11/2005	20	0	2:23:29	Auto GG Trip, X6, index 23	GG Syst.
44	3/11/2005	20	0	1:35:18	Normal shutdown, test completed.	---
45	3/14/2005	20	0	0:40:35	Auto trip on oxygen skid	O_2 Syst.
46	3/14/2005	20	0	0:01:04	Auto GG Trip, X6, index 8	O_2 Syst.
47	3/14/2005	20	0	2:48:34	Normal shutdown, test completed.	---
48	3/15/2005	40	0.5	2:02:49	Auto GG Trip, X6, index 23	GG Syst.
49	3/15/2005	81	1.5	2:16:42	Auto GG Trip, X6,index 22	Elec. Syst.
50	3/16/2005	45	0.6	4:10:11	Normal shutdown, test completed.	---
51	3/17/2005	20	0	0:01:01	Auto GG Trip, X5, index 1	GG Syst.
52	3/17/2005	20	0	0:01:01	Auto GG Trip, X5, index 1	GG Syst.
53	3/17/2005	20	0	0:01:01	Auto GG Trip, X5, index 1	GG Syst.
54	3/17/2005	40	0.5	5:14:46	Normal shutdown, test completed.	---
55	3/18/2005	40	0	0:50:00	Auto trip on oxygen skid	O_2 Syst.
56	3/18/2005	50	0.6	4:20:00	Loss of elect. power, 52L breaker tripped	Elec. Syst.
57	3/23/2005	50	0.6	7:03:00	Normal shutdown, test completed.	---
58	3/24/2005	20	0	0:26:00	Auto GG Trip, X5, index 9	GG Syst.
59	3/24/2005	20	0	0:05:00	Auto GG Trip, X5, index 9	GG Syst.
60	3/24/2005	50	0.6	6:37:00	Loss of elect. power, 52L breaker tripped	Elec. Syst.
61	3/28/2005	35	0	0:54:00	Auto trip on oxygen skid	O_2 Syst.
62	3/28/2005	20	0	2:06:00	Normal shutdown, test completed.	---
63	3/29/2005	20	0	0:01:01	Auto GG Trip, X5, index 3	GG Syst.
64	3/29/2005	40	0.5	5:17:21	Normal shutdown, test completed.	---
65	4/4/2005	35	0.5	5:58:02	Auto GG Trip, X6, index 49	GG Syst.
66	4/5/2005	20	0	0:01:18	Auto GG Trip, X5, index 4	GG Syst.
67	4/5/2005	20	0	0:48:29	Auto GG Trip, X5, index 32	H_2O syst.
68	4/6/2005	35	0.6	2:23:49	Normal shutdown, test completed.	---
69	4/7/2005	30	0	1:03:46	Loss of elect. power, 52L breaker tripped	Elec. Syst.
70	4/7/2005	20	0	0:32:39	Auto trip on oxygen skid	O_2 Syst.
71	4/7/2005	65	1.5	1:16:40	Loss of elect. power, 52L breaker tripped	Elec. Syst.
72	4/7/2005	65	1.5	2:20:11	Normal shutdown, clogged inline filter.	H2O syst.
73	4/8/2005	20	0	0:41:37	Auto trip on oxygen skid	O_2 Syst.
74	4/8/2005	25	0.5	0:53:00	Loss of elect. power, 52L breaker tripped	Elec. Syst.
75	4/8/2005	0	0	0:00:24	Testing new sequence, test completed.	---
76	4/8/2005	75	2.2	2:33:59	Normal shutdown, test completed.	---
77	4/13/2005	20	0	0:01:18	Auto GG Trip, X5, index 4	GG Syst.
78	4/13/2005	35	0	1:22:41	Loss of elect. power, 52L breaker tripped	Elec. Syst.
79	4/13/2005	20	0	0:24:02	Auto trip on oxygen skid	O_2 Syst.

Run No.	Start Date	GG Output, %[†]	MW$_e$	Run Time	Shutdown Comments	Shutdwn Cause
80	4/13/2005	88	2.3	1:52:42	Normal shutdown, test completed.	---
81	4/14/2005	20	0	0:01:14	Auto GG Trip, X5, index 1	GG Syst.
82	4/14/2005	45	1	1:59:17	Loss of elect. power to the PLC.	Elec. Syst.
83	4/15/2005	40	0	1:28:26	Loss of elect. power, 52L breaker tripped	Elec. Syst.
84	4/18/2005	20	0	0:20:15	Auto GG Trip, X5, index 4	GG Syst.
85	4/18/2005	20	0	0:01:05	Auto GG Trip, X5, index 8	GG Syst.
86	4/18/2005	77	2	3:05:53	Normal shutdown, test completed.	---
87	4/19/2005	25	0	1:00:13	Auto trip on oxygen skid	O_2 Syst.
88	4/19/2005	72	2	6:36:19	Normal shutdown, test completed.	---
89	4/20/2005	20	0	0:36:10	Auto trip on oxygen skid	O_2 Syst.
90	4/20/2005	20	0	0:16:05	Auto trip on oxygen skid	O_2 Syst.
91	4/21/2005	42	1.2	8:15:18	Normal shutdown, test completed.	---
92	4/26/2005	42	1.2	3:46:03	Auto trip on oxygen skid	O_2 Syst.
93	4/27/2005	42	1.2	7:15:32	Normal shutdown, test completed.	---
94	4/28/2005	20	0	0:50:20	Auto GG Trip, X5, index 21	O_2 Syst.
95	4/28/2005	42	1.2	4:25:27	Auto GG Trip, X6, index 22	T/G Syst.
96	4/29/2005	20	0	0:02:35	Normal shutdown to repair water leak	GG Syst.
97	5/2/2005	80	2.2	2:44:17	Auto GG Trip, X6, index 22	T/G Syst.
98	5/2/2005	50	0	0:17:01	Tripped on undocumented reason.	??
99	5/4/2005	20	0	0:03:13	Normal shutdown, test completed.	---
100	5/5/2005	35	0	1:19:48	Auto GG Trip, X5, index 1	GG Syst.
101	5/5/2005	40	1.3	8:27:33	Normal shutdown, test completed.	---
102	5/6/2005	40	1.2	4:30:41	Auto trip on oxygen skid	O_2 Syst.
103	5/6/2005	45	1.3	1:37:01	Normal shutdown, test completed.	---
104	5/9/2005	20	0	1:01:47	Auto trip on oxygen skid	O_2 Syst.
105	5/9/2005	40	1.2	1:34:13	Auto GG Trip due to operator error	Human
106	5/10/2005	71	1.1	8:06:30	Normal shutdown, test completed.	---
107	5/11/2005	25	0	1:15:41	Normal shutdown, test completed.	---
108	5/11/2005	40	1.2	4:53:03	Auto trip on oxygen skid	O_2 Syst.
109	5/12/2005	20	0	0:01:47	Normal shutdown, ignition/low-fire test	---
110	5/13/2005	20	0	0:01:50	Normal shutdown, ignition/low-fire test	---
111	5/13/2005	20	0	0:01:13	Normal shutdown, ignition/low-fire test	---
112	5/13/2005	20	0	0:01:47	Normal shutdown, ignition/low-fire test	---
113	5/16/2005	20	0	0:31:43	Auto trip on oxygen skid	O_2 Syst.
114	5/16/2005	35	0	2:31:42	CW pump motor electrical short.	Elec. Syst.
115	5/17/2005	20	0	0:01:00	Auto GG Trip, X5, index 24	GG Syst.
116	5/17/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
117	5/26/2005	20	0	0:56:06	Auto trip on oxygen skid	O_2 Syst.
118	5/27/2005	20	0	0:01:00	Auto GG Trip, X5, index 16	GG Syst.
119	5/27/2005	20	0	0:04:46	Manual shutdown, low T & P steam	GG Syst.

Run No.	Start Date	GG Output, %[†]	MWe	Run Time	Shutdown Comments	Shutdwn Cause
120	5/27/2005	0	0	0:00:53	Auto GG Trip, X4, index 14	GG Syst.
121	5/27/2005	0	0	0:01:02	Auto GG Trip, X4, index 14	GG Syst.
122	5/31/2005	0	0	0:00:53	Auto GG Trip, X4, index 14	GG Syst.
123	5/31/2005	0	0	0:00:53	Auto GG Trip, X4, index 14	GG Syst.
124	5/31/2005	20-70	0.5	4:56:38	Auto GG Trip, X6, index 23	GG Syst.
125	6/1/2005	20	0	0:36:22	Auto trip on oxygen skid	O_2 Syst.
126	6/1/2005	20-50	0.8	3:23:19	Normal shutdown, test completed.	---
127	6/2/2005	20-74	1	3:15:36	Auto GG Trip, X6, index 23	GG Syst.
128	6/3/2005	20	0	0:10:33	Normal shutdown, test completed.	---
129	6/3/2005	30	0.5	2:50:01	Auto trip on oxygen skid	O_2 Syst.
130	6/6/2005	20	0	0:17:06	Shutdown due to gas compressor leak	NG Syst.
131	6/6/2005	20-48	1.4	5:59:25	Auto trip on oxygen skid	O_2 Syst.
132	6/7/2005	76	2.5	8:01:19	Normal shutdown, end of day.	---
133	6/9/2005	30	0.5	3:56:58	Auto trip on oxygen skid	O_2 Syst.
134	6/9/2005	0	0	0:00:10	Auto GG Trip, X3, index 8	O_2 Syst.
135	6/9/2005	30	0.5	3:07:07	Normal shutdown, end of day.	---
136	6/10/2005	30	0.6	2:36:14	Auto trip on oxygen skid	O_2 Syst.
137	6/13/2005	30	0.6	2:36:38	Auto trip on oxygen skid	O_2 Syst.
138	6/13/2005	30	0.6	1:15:42	Auto trip on oxygen skid	O_2 Syst.
139	6/13/2005	30	0.6	0:11:40	Auto GG Trip, X6, index 32,	H_2O syst.
140	6/14/2005	30	0.6	2:47:11	Auto trip on oxygen skid	O_2 Syst.
141	6/14/2005	35	0.8	5:34:32	Normal shutdown, end of day.	---
142	6/15/2005	0	0	0:00:27	Main steam line safety valve lifted	Stm. Syst.
143	6/15/2005	0	0	0:00:56	Main steam line safety valve lifted	Stm. Syst.
144	6/20/2005	35	0.8	3:47:25	Normal shutdown, end of day.	---
145	6/21/2005	35	0.8	9:13:59	Normal shutdown, end of day.	---
146	6/22/2005	20	0	0:16:08	Normal shutdown to repair water leak	GG Syst.
147	6/22/2005	0	0	0:01:56	Auto GG Trip, ignition failed.	GG Syst.
148	6/22/2005	35	0.8	6:32:39	Normal shutdown, end of day.	---
149	6/24/2005	35	0.8	12:05:02	Normal shutdown, end of day.	---
150	6/27/2005	35	0.8	7:19:20	Auto trip on oxygen skid	O_2 Syst.
151	6/28/2005	35-70	0.8-2.2	9:14:54	Normal shutdown, end of day.	---
152	6/29/2005	0	0	0:00:00	Auto GG Trip, X1, index 10	GG Syst.
153	6/29/2005	0	0	0:00:13	Auto GG Trip, X2, index 25, operator error	Human
154	6/29/2005	25	0	1:24:10	Auto GG Trip, X6, index 22, operator error	Human
155	6/29/2005	33	0.75	4:01:37	Auto trip on oxygen skid	O_2 Syst.
156	6/30/2005	0	0	0:00:01	Auto GG Trip, X1, index 8	O_2 Syst.
157	6/30/2005	0	0	0:00:28	Auto GG Trip, X1, index 8	O_2 Syst.
158	6/30/2005	0	0	0:00:02	Auto GG Trip, X1, index 8	O_2 Syst.
159	7/1/2005	20	0	0:19:37	Normal shutdown, O2 pump malfunction.	O_2 Syst.

Run No.	Start Date	GG Output, %[†]	MW$_e$	Run Time	Shutdown Comments	Shutdwn Cause
160	7/1/2005	20	0	0:00:39	Auto GG Trip, X5, index 21	O_2 Syst.
161	7/1/2005	20	0	2:12:18	Normal shutdown, end of day.	---
162	7/7/2005	20	0	1:13:01	Normal shutdown, comp. hard drive full	---
163	7/7/2005	20	0	0:07:06	Auto GG Trip, X5, index 21	O_2 Syst.
164	7/7/2005	0	0	0:00:06	Auto GG Trip, X2, index 25	N_2 Syst.
165	7/7/2005	0	0	0:00:09	Auto GG Trip, X2, index 25	N_2 Syst.
166	7/7/2005	35	0.8	2:04:29	Normal shutdown, main O2 chk valve leak	GG Syst.
167	7/8/2005	20	0	0:08:02	Auto GG Trip, X5, index 21	O_2 Syst.
168	7/8/2005	35	0.8	6:44:17	Normal shutdown, end of day.	---
169	7/11/2005	20	0	0:00:45	Normal shutdown, steam drain leak	Stm. Syst.
170	7/11/2005	20	0	0:06:42	Auto GG Trip, X5, index 21	O_2 Syst.
171	7/11/2005	35	0.8	7:31:35	Normal shutdown, end of day.	---
172	7/12/2005	20	0	0:09:43	Auto GG Trip, X6, index 8	O_2 Syst.
173	7/12/2005	35	0.8	8:56:26	Low-pressure trip on TG lube oil pump	T/G Syst.
174	7/14/2005	20	0	0:01:38	Auto GG Trip, X6, index 2	GG Syst.
175	7/14/2005	65	1.7	5:58:49	Auto GG Trip, X6, index 7	NG Syst.
176	7/18/2005	20	0	0:18:07	Normal shutdown, test completed	---
177	7/19/2005	70	2.1	8:12:11	Normal shutdown, end of day.	---
178	7/20/2005	25	0	0:20:09	Auto GG Trip, X6, index 8	O_2 Syst.
179	7/21/2005	35	0.8	6:33:34	Normal shutdown, end of day.	---
180	7/22/2005	25	0	0:08:19	Auto GG Trip, X6, index 8	O_2 Syst.
181	7/22/2005	40	1	6:31:14	Normal shutdown, end of day.	---
182	7/25/2005	45	1.1	2:30:25	Auto GG Trip, X6, index 8	O_2 Syst.
183	7/25/2005	20	0	0:02:38	Auto GG Trip, X6, index 8	O_2 Syst.
184	7/26/2005	25	0	0:14:28	Auto GG Trip, X6, index 8	O_2 Syst.
185	7/26/2005	25	0	0:11:05	Auto GG Trip, X6, index 8	O_2 Syst.
186	7/26/2005	20	0	0:26:30	Auto GG Trip, X5, index 21	O_2 Syst.
187	7/26/2005	20	0	1:23:42	Normal shutdown, end of day.	---
188	7/27/2005	0	0	0:00:28	Auto GG Trip, X4, index 14, operator error	Human
189	7/27/2005	40	0.8	27:03:00	Normal shutdown, O2 pump malfunction.	O_2 Syst.
190	7/28/2005	25	0	0:19:11	Normal shutdown, O2 pump malfunction.	O_2 Syst.
191	7/28/2005	55	1.5	18:02:48	Normal Shutdown, end of Week	---
192	8/26/2005	20	0	0:00:35	Auto GG Trip, X5, index 3	GG Syst.
193	8/26/2005	20	0	0:02:09	Auto GG Trip, X5, index 3	GG Syst.
194	8/26/2005	20	0	0:02:09	Auto GG Trip, X6, index 4	GG Syst.
195	8/26/2005	20	0	0:06:00	Auto GG Trip, X6, index 4	GG Syst.
196	8/26/2005	25	0	1:31:53	Auto GG Trip, X6, index 10	GG Syst.
197	8/29/2005	38	0.8	3:42:03	Normal shutdown, end of day.	---
198	9/1/2005	35	0.6	3:51:39	Normal shutdown, end of day.	---
199	9/2/2005	35	0.7	6:30:20	Normal shutdown, end of day.	---

Run No.	Start Date	GG Output, %[†]	MW$_e$	Run Time	Shutdown Comments	Shutdwn Cause
200	9/6/2005	25	0	1:39:34	Auto GG Trip, X6, index 22	GG Syst.
201	9/6/2005	60	1.6	10:10:19	Auto GG Trip, X6, index 36	O_2 Syst.
202	9/7/2005	35	0.7	12:27:43	Loss of power, 52L breaker tripped open	Elec. Syst.
203	9/13/2005	35	0.7	19:31:52	Normal shutdown to repair water leak	GG Syst.
204	9/14/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
205	9/14/2005	0	0	0:00:36	Auto GG Trip, X4, index 14	GG Syst.
206	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
207	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
208	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
209	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
210	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
211	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
212	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
213	9/14/2005	0	0	0:00:35	Auto GG Trip, X5, index 16	GG Syst.
214	9/15/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
215	9/15/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
216	9/15/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
217	9/15/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
218	9/15/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
219	9/15/2005	0	0	0:00:28	Auto GG Trip, X4, index 14	GG Syst.
220	9/15/2005	20	0	0:01:43	Auto GG Trip, X5, index 50	GG Syst.
221	9/15/2005	20	0	0:06:14	Auto GG Trip, X5, Index 4.	GG Syst.
222	9/15/2005	20	0	0:05:58	Auto GG Trip, X5, index 0	GG Syst.
223	9/20/2005	20	0	0:59:26	Normal shutdown to repair water leak	GG Syst.
224	9/20/2005	33	0.65	15:28:47	Normal shutdown to repair water leak	GG Syst.
225	9/21/2005	0	0	0:00:28	Auto GG Trip, X4, index 14, operator error	Human
226	9/21/2005	35	0.9	18:03:28	Normal shutdown, O2 pump malfunction.	O_2 Syst.
227	9/22/2005	25	0	0:39:08	Auto GG Trip, X6, index 22	GG Syst.
228	9/22/2005	35	0.85	17:05:24	Normal Shutdown, end of Week	---
229	9/26/2005	0	0	0:00:35	Auto GG Trip, X5, Index 3	GG Syst.
230	9/26/2005	20	0	0:02:54	Normal shutdown to repair water leak	GG Syst.
231	9/26/2005	35	0.85	27:38:08	Normal shutdown to repair water leaks	GG Syst.
232	9/27/2005	35	0.85	34:37:28	Auto GG Trip, X6, index 36	O_2 Syst.
233	9/29/2005	25	0	0:49:30	Normal shutdown to repair steam leak	Stm. Syst.
234	9/29/2005	40	1.1	5:30:29	Normal shutdown to repair O2 pump leak	O_2 Syst.
235	10/15/2005	20	0	0:18:06	Auto GG Trip, X5, index 10	H_2O Syst.
236	10/15/2005	20	0	0:00:38	Auto GG Trip, X5, index 3	GG Syst.
237	10/15/2005	20	0	0:00:56	Auto GG Trip, X5, index 3	GG Syst.
238	10/15/2005	35	0.8	42:09:27	Auto GG Trip, X6, index 7	NG Syst.
239	10/17/2005	40	1.1	24:14:07	Auto GG Trip, X6, index 8	O_2 Syst.

Run No.	Start Date	GG Output, %[†]	MWe	Run Time	Shutdown Comments	Shutdwn Cause
240	10/18/2005	20	0	0:00:38	Normal shutdown, operator error	Human
241	10/18/2005	0	0	0:00:28	Auto GG Trip, X4, index 14, operator error	Human
242	10/18/2005	20	0	0:09:00	Auto GG Trip, X5, index 10	H_2O Syst.
243	10/18/2005	40	1.1	39:24:19	Auto trip on oxygen skid	O_2 Syst.
244	10/20/2005	0	0	0:00:00	Auto GG Trip, X1, index 25	N_2 Syst.
245	10/20/2005	0	0	0:00:00	Auto GG Trip, X1, index 25	N_2 Syst.
246	10/20/2005	40	1.1	7:12:26	Normal shutdown, end of week.	---
247	10/24/2005	20	0	0:00:35	Auto GG Trip, X5, index 2	GG Syst.
248	10/24/2005	20	0	0:00:34	Auto GG Trip, X5, index 16	GG Syst.
249	10/24/2005	20	0	0:21:15	Normal shutdown to repair water leaks	GG Syst.
250	10/24/2005	0	0	0:00:28	Auto GG Trip, X4, index 14, operator error	Human
251	10/24/2005	20	0	0:01:23	Auto GG Trip, X5, index 20	NG Syst.
252	10/24/2005	33	0.6	8:13:12	Normal shutdown to repair water leaks	GG Syst.
253	10/25/2005	20	0	0:42:46	Auto GG Trip, X5, index 2	GG Syst.
254	10/25/2005	0	0	0:00:24	Auto GG Trip, X3, index 13	GG Syst.
255	10/25/2005	65	2	7:09:57	Auto GG Trip, X6, index 36	O_2 Syst.
256	10/26/2005	75	2.7	3:42:16	Auto GG Trip, X6, index 7	NG Syst.
257	10/26/2005	40	1.2	34:40:05	Normal shutdown, end of week.	---
258	10/31/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
259	10/31/2005	33	0.9	36:21:27	Normal shutdown to repair water leaks	GG Syst.
260	11/2/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
261	11/2/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
262	11/2/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
263	11/2/2005	25	0	1:03:39	Auto GG Trip, X6, index 4	GG Syst.
264	11/3/2005	0	0	0:00:00	Failure to start, Troubleshooting problem.	GG Syst.
265	11/3/2005	0	0	0:00:00	Failure to start, Troubleshooting problem.	GG Syst.
266	11/3/2005	0	0	0:00:00	Failure to start, Troubleshooting problem.	GG Syst.
267	11/3/2005	0	0	0:00:00	Failure to start, Troubleshooting problem.	GG Syst.
268	11/3/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
269	11/7/2005	35	1	8:45:03	Auto GG Trip, X6, index 4	GG Syst.
270	11/8/2005	35	1	47:04:12	Auto GG Trip, X6, index 7	NG Syst.
271	11/10/2005	35	1	7:51:42	Normal shutdown, low O2 tank level.	---
272	11/11/2005	35	1	6:10:18	Normal shutdown, end of demonstration.	---
273	11/14/2005	0	0	0:02:57	Normal shutdown to repair water leaks.	GG Syst.
274	11/14/2005	0	0	0:00:22	Auto GG Trip, X5, index 16	GG Syst.
275	11/14/2005	45	1.2	1:30:58	Auto GG Trip, X6, index 7	NG Syst.
276	11/15/2005	35	1	26:57:09	Normal shutdown, low O2 tank level	---
277	11/16/2005	0	0	0:00:22	Normal shutdown, operator error	Human
278	11/16/2005	33	0.7	16:00:34	Normal shutdown, low O2 tank level	---
279	11/16/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.

Run No.	Start Date	GG Output, %[†]	MW$_e$	Run Time	Shutdown Comments	Shutdwn Cause
280	11/17/2005	30	0.6	11:10:33	Normal shutdown, low O2 tank level	---
281	11/17/2005	20	0	0:00:34	Normal shutdown, operator error	Human
282	11/17/2005	30	0	0:48:17	Auto GG Trip, X6, index 4	GG Syst.
283	11/17/2005	35	1	13:02:52	Normal shutdown, end of week.	---
284	11/28/2005	20	0	0:15:31	Auto trip on oxygen skid	O_2 Syst.
285	11/28/2005	0	0	0:00:07	Auto GG Trip, X3, index 13	GG Syst.
286	11/28/2005	20	0	0:01:53	Auto GG Trip, X5, index 50	GG Syst.
287	11/28/2005	32	0.8	105:21:10	Auto GG Trip, X6, index 36	O2 Syst.
288	12/5/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
289	12/5/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
290	12/5/2005	32	0.8	2:37:25	Auto GG Trip, X6, index 46	GG Syst.
291	12/6/2005	0	0	0:00:22	Auto GG Trip, X4, index 10	GG Syst.
292	12/13/2005	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
293	12/13/2005	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
294	12/13/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
295	12/13/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
296	12/13/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
297	12/13/2005	20	0	1:19:00	Auto GG Trip, X6, index 46	GG Syst.
298	12/13/2005	33	0	0:15:51	Auto GG Trip, X6, index 46	GG Syst.
299	12/13/2005	35	0.7	5:24:43	Normal shutdown, end of day.	---
300	12/14/2005	20	0	0:43:37	Normal shutdown to repair steam leak	---
301	12/14/2005	0	0	0:00:10	Auto GG Trip, X2, index 25	N_2 Syst.
302	12/14/2005	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
303	12/14/2005	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
304	12/14/2005	35	0.9	10:41:10	Normal shutdown, end of day.	---
305	12/15/2005	20	0	0:02:34	Normal shutdown to repair steam leak	Stm. Syst.
306	12/15/2005	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
307	12/15/2005	0	0	0:00:17	Auto GG Trip, X4, Index 14	GG Syst.
308	12/15/2005	20	0	0:05:47	Auto trip on oxygen skid	O_2 Syst.
309	12/15/2005	0	0	0:00:16	Auto GG Trip, X4, index 30	GG Syst.
310	12/15/2005	35	0.8	5:02:21	Normal shutdown, end of day.	---
311	12/16/2005	0	0	0:00:21	Auto GG Trip, X5, index 16	GG Syst.
312	12/16/2005	0	0	0:00:22	Auto GG Trip, X5, index 16	GG Syst.
313	12/16/2005	0	0	0:00:22	Auto GG Trip, X5, index 16	GG Syst.
314	12/16/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
315	12/16/2005	0	0	0:00:22	Auto GG Trip, X5, index 10	GG Syst.
316	12/16/2005	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
317	12/16/2005	20	0	0:51:49	Auto GG Trip, X6, index 4	GG Syst.
318	12/16/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
319	12/16/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.

Run No.	Start Date	GG Output, %[†]	GG Output, MW_e	Run Time	Shutdown Comments	Shutdwn Cause
320	12/16/2005	0	0	0:00:18	Auto GG Trip, X4, index 30	GG Syst.
321	12/16/2005	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
322	12/16/2005	0	0	0:00:00	Auto GG Trip, X0, index 8	O_2 Syst.
323	12/16/2005	0	0	0:00:11	Auto GG Trip, X4, index 13	GG Syst.
324	12/16/2005	20	0	0:01:37	Normal shutdown, low steam temp.	---
325	12/16/2005	0	0	0:00:00	Auto GG Trip, X0, index 8	O_2 Syst.
326	12/16/2005	0	0	0:00:00	Operator error	Human
327	12/16/2005	0	0	0:00:00	Operator error	Human
328	12/16/2005	0	0	0:00:15	Auto GG Trip, X4, index 31	GG Syst.
329	12/20/2005	40	1.1	6:05:57	Auto GG Trip, X6, index 7	NG Syst.
330	12/20/2005	35	0.8	5:43:07	Normal shutdown, end of day.	---
331	12/21/2005	20	0	0:12:24	Auto GG Trip, X5, index 10	H_2O Syst.
332	12/21/2005	0	0	0:00:22	Auto GG Trip, X5, index 16	GG Syst.
333	12/21/2005	0	0	0:00:22	Auto GG Trip, X5, index 16	GG Syst.
334	12/21/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
335	12/21/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
336	12/21/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
337	12/21/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
338	12/22/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
339	12/22/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
340	12/22/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
341	12/22/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
342	12/22/2005	0	0	0:00:11	Auto GG Trip, X3, index 30	GG Syst.
343	12/22/2005	0	0	0:00:15	Auto GG Trip, X4, index 14	GG Syst.
344	12/22/2005	20	0	0:09:27	Normal shutdown for testing of igniter	---
345	12/22/2005	20	0	1:01:09	Normal shutdown, end of day.	---
346	12/23/2005	35	0.9	3:19:13	Normal shutdown, end of day.	---
347	1/2/2006	0	0	0:01:21	Slow GG pressure rise, no ignition	GG Syst.
348	1/2/2006	35	0.9	6:08:09	Auto GG Trip, X6, index 8	O_2 Syst.
349	1/2/2006	0	0	0:00:11	Auto GG Trip, X6, index 24	GG Syst.
350	1/2/2006	35	0.9	2:03:34	Normal shutdown, end of day.	---
351	1/3/2006	20	0	0:20:50	Auto trip on oxygen skid	O_2 Syst.
352	1/3/2006	0	0	0:00:00	Auto GG Trip, X0, index 0	O_2 Syst.
353	1/3/2006	35	0.9	4:53:36	Normal shutdown, inspect for water leak.	---
354	1/4/2006	0	0	0:00:00	Skipped run	---
355	1/4/2006	79	2.2	3:18:15	Auto GG Trip, X6, index 50	GG Syst.
356	1/4/2006	73	2.1	5:20:08	Normal shutdown, end of day.	---
357	1/5/2006	70	2.5	7:52:13	Normal shutdown, end of day.	---
358	1/6/2006	0	0	0:00:15	Auto GG Trip, X4, index 8	O_2 Syst.
359	1/6/2006	0	0	0:00:00	Auto GG Trip, X1, index 8	O_2 Syst.

Run No.	Start Date	GG Output, %[†]	MW$_e$	Run Time	Shutdown Comments	Shutdwn Cause
360	1/6/2006	40	1.1	5:18:16	Normal shutdown, end of day.	---
361	1/9/2006	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
362	1/9/2006	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
363	1/9/2006	0	0	0:00:46	Normal shutdown to repair TC failure	GG Syst.
364	1/9/2006	35	0.9	5:04:14	Normal shutdown, end of day.	---
365	1/10/2006	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
366	1/10/2006	50	1.55	4:06:42	Normal shutdown for to site tour	---
367	1/11/2006	50	1.55	7:27:40	Normal shutdown, end of day.	---
368	1/12/2006	60	1.95	3:09:29	Auto trip on oxygen skid	O_2 Syst.
369	1/12/2006	35	0.9	3:57:49	Normal shutdown, end of day.	---
370	1/13/2006	0	0	0:00:00	Operator error	Human
371	1/13/2006	35	0	0:28:53	Auto trip on oxygen skid	O_2 Syst.
372	1/16/2006	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
373	1/16/2006	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
374	1/17/2006	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
375	1/17/2006	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
376	1/17/2006	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
377	1/17/2006	35	0.9	9:32:57	Normal shutdown, end of day.	---
378	1/18/2006	60	1.8	15:19:40	Normal shutdown, end of day.	---
379	1/19/2006	0	0	0:00:11	Auto GG Trip, X3, index 13	GG Syst.
380	1/19/2006	20	0	0:06:22	Normal shutdown to repair water leak	GG Syst.
381	1/19/2006	35	0.9	4:22:22	Shutdown due to loss of HMI computer	GG Syst.
382	1/20/2006	20	0	0:11:25	Auto GG Trip, X5, index 10	H_2O Syst.
383	1/20/2006	35	0.9	9:17:23	Normal shutdown, end of day.	---
384	1/23/2006	40	1.1	2:36:56	Normal shutdown, end of day.	---
385	1/24/2006	0	0	0:00:00	Skipped run	---
386	1/24/2006	40	1.1	6:30:12	Normal shutdown, end of day.	---
387	1/26/2006	35	0.9	10:01:28	Normal shutdown, end of day.	---
388	1/27/2006	30	0.7	8:53:09	Auto trip on oxygen skid	O_2 Syst.
389	1/31/2006	35	0.9	12:04:59	Normal shutdown, end of day.	---
390	2/1/2006	35	0.8	15:03:12	Normal shutdown, end of day.	---
391	2/2/2006	35	0.9	12:02:59	Normal shutdown, end of day.	---
392	2/3/2006	30	0.6	6:02:34	Normal shutdown, low O2 tank level	---
393	2/6/2006	30	0.6	12:01:12	Normal shutdown, end of day.	---
394	2/7/2006	20	0	0:38:50	Normal shutdown, bad flow meter	GG Syst.
395	2/7/2006	30	0.6	7:39:27	Normal shutdown, end of day.	---
396	2/8/2006	35	0.8	8:09:04	Normal shutdown, end of day.	---
397	2/14/2006	0	0	0:00:57	Auto GG Trip, X5, index 47	GG Syst.
398	2/14/2006	20	0	0:09:29	Normal shutdown to repair steam leak	Stm. Syst.
399	2/14/2006	60	1.9	5:37:04	Normal shutdown, end of day.	---

Run No.	Start Date	GG Output, %[†]	MW$_e$	Run Time	Shutdown Comments	Shutdwn Cause
400	2/15/2006	0	0	0:00:11	Auto GG Trip, X3, index 25	N_2 Syst.
401	2/15/2006	35	0.8	3:05:30	Normal shutdown, end of day.	---
402	2/17/2006	35	0.9	3:58:17	Normal shutdown, end of day.	---
403	2/21/2006	40	1.1	6:32:07	Normal shutdown, end of day.	---
404	3/1/2006	0	0	0:00:16	Auto GG Trip, X4, index 30	GG Syst.
405	3/1/2006	0	0	0:00:15	Auto GG Trip, X4, index 13	GG Syst.
406	3/1/2006	50	1.55	7:21:54	Normal shutdown, end of day.	---
407	3/3/2006	40	0	1:43:20	Normal shutdown, end of day.	---
408	3/6/2006	40	1.1	2:27:02	Normal shutdown, end of day.	---
409	3/7/2006	70	2	6:17:06	Auto GG Trip, X6, index 36	O_2 Syst.
410	3/24/2006	20	0	1:27:15	Normal shutdown, end of day.	---
411	3/29/2006	70	2.3	3:06:27	Auto trip on oxygen skid	O_2 Syst.
412	3/29/2006	20	0	0:14:47	Auto trip on oxygen skid	O_2 Syst.
413	3/29/2006	70	2.3	0:37:31	Auto trip on oxygen skid	O_2 Syst.
			Total	1333:36:56		

[†] The percentage of full power outputs as given in this table are based on the GG fuel flow meter and may be lower than actual values by about 15 % if the gas supply company's gas meter is assumed to be correct.